Appendices

to

FINAL S.E.I.S

for

The Puget Sound Commercial Geoduck Fishery

Appendices

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Appendix 1

DRAFT
2000 Geoduck Atlas

Atlas of Major Geoduck Tracts of Puget Sound

April 2000

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The Washington Department of Fish and Wildlife (WDFW) began SCUBA surveys in Puget Sound for subtidal geoducks and other subtidal shellfish species in 1967. These annual surveys have continued to the present. Treaty tribes began subtidal geoduck surveys in 1996. The geoduck atlas is a compilation and summary of all of these surveys and other information relevant to the geoduck clam fishery.

All of Puget Sound (defined as all marine waters east of Cape Flattery and south of the United States/Canada International Border) has not been thoroughly searched for subtidal geoducks. Most of the survey effort has taken place in waters of Admiralty Inlet, Central Sound, South Sound, and Hood Canal. Very few geoduck tracts shown in this Atlas are located in the western portion of the Strait of Juan de Fuca, San Juan Islands, and north Puget Sound. The initial survey work in these regions did not result in the discovery of numerous large tracts like those of the rest of Puget Sound. Survey work completed by WDFW for geoducks and other subtidal species has shown that geoducks do exist in the western portion of the Strait, the San Juans, and North Sound, but not in the high concentrations of the other regions.

The reader should keep in mind that this Atlas does not always show areas that were searched, but found to have no geoducks. Therefore, blank areas in the Atlas could either have been searched and found not to have geoducks or were never searched and, therefore, the geoduck distribution is unknown. Virtually all of the survey work was confined to the area between the minus 18 foot and minus 70 foot depth contours, corrected to mean lower low water (MLLW). In many locations geoducks extend shoreward and seaward of the survey zone. Geoducks have been found as deep as 360 feet in certain areas of Puget Sound. Geoduck distribution is more extensive than what is shown in this Atlas.

The Atlas is composed of two sections. The first is a series of vicinity maps showing the geoduck tracts. The maps in the Atlas are intended to provide the general location of geoduck tracts. These maps are small scale, tract boundaries may be hand fit estimations, and figures may be distorted from printing. Readers should keep this in mind when making decisions regarding the exact location and size of geoduck tracts.

The second portion of this Atlas is a table which lists all the numbered tracts which correspond to the tracts on the vicinity maps. All known geoduck tracts have been assigned a five digit number. An additional digit was added in 1997 for data management purposes. The Atlas table also includes information on tract size, geoduck population estimates, fishing history, and current status of the tracts. Estimates of total numbers, biomass, geoduck density, and mean weight have been rounded. In some cases, an estimate of poundage is given for a tract in which no geoduck samples were taken. For these tracts, the poundage has been estimated assuming an average weight of 2.0 pounds per geoduck, the Puget Sound average.

Tracts with no quantitative population information are designated as (X)-beds and have been assigned a status of "11" in the tables. Some of these areas were surveyed by the Point Whitney dive team for species other than geoducks, and only the presence or absence of geoducks was recorded. The locations of some status "11" beds were obtained from commercial fishers. The quantitative information for the remaining tracts varies depending upon the year and type of survey, as noted in tabular comments. In some cases the number of transects is low, or the survey was performed when the geoduck siphon "show" factor was highly variable, and the information does not meet precision requirements to qualify a tract for fishing.

During certain times of the year some tracts should not be harvested due to potential risks to spawning herring. These beds have been assigned a status of "12" and the recommended closure period has been noted. Herring spawning areas and times can be found in the Washington State Baitfish Stock Status Report. Fifteen tracts, which have been fished out, are part of a long-term recovery study. The purpose of this study is to empirically verify changes in geoduck density (recovery) following fishing events. A series of post-fishing surveys are conducted to determine rates of recovery. Recovery study tracts have been assigned a status of "9" and will not be available to fish until their respective pre-fishing densities have been reached. The pre-fishing density in the Atlas table is adjusted with a 0.75 siphon "show factor."

The Atlas is updated once a year, during the winter. All new beds discovered are added to the list along with changes due to fishing, changes resulting from Department of Health (DOH) certification, results of tract surveys, etc. The biomass and average geoduck density estimates for tracts being fished are annually revised to reflect harvest from through December 31 of the previous year. This allows harvest information to be received and compiled for March publication of the Atlas. Once a tract is fished out, the biomass reported will be the pre-fishing biomass estimate minus the total harvest amount, and this estimate is not revised until an adequate SCUBA survey is completed.

The tabular data are provided only as a statewide overview of the geoduck resource. Individual tract data from WDFW dive surveys generally include far more detailed information, including: transect locations, water depths, substrate types, presence/absence of other plant and animal species, relative difficulty of digging geoducks, geoduck valve lengths and weights from dig samples, geoduck siphon weights, presence/absence of geoducks in shallow and deep off-tract areas which were not surveyed quantitatively, and eelgrass survey data. More complete information for many of the tracts can be obtained by resource managers from the WDFW Point Whitney Shellfish Laboratory in Brinnon, Washington, telephone (360) 796-4601.

Acknowledgement

We appreciate all of those who have contributed to the Geoduck Atlas each year.

Definitions

MLLW - Mean Lower Low Water (0.0 ft. tide level). Water depths reported are typically corrected to a 0.0 ft. or MLLW tide level

MHW - Mean High Water. 11 ft. tide level for Puget Sound.

STP - Sewage Treatment Plant.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND - 2000

Index Table for Area Maps and Figures

Index Table for Area Maps and Figures (cont.)

Figure Number	Geoduck Tracts	Geoduck Region
29	03900; 03940; 03950	NS
	05450; 06000	CS
30	06000; 06100; 06300-06600; 07400; 07500	CS
31	06500-07370; 07900-08250	CS
32	06100; 06600; 07400-07950; 08200-08400; 08700; 08800	CS
33	07850; 07900; 08200-08700	CS
	09000-09200; 09400; 09600-09800; 10000-10100	SS
34	09500; 09550; 09700-10400	SS
35	09200; 09300; 09500; 09550; 10300; 10350; 10450-10600; 10800-11250; 11300-11750	SS
36	10700-11300; 11950-13850; 14300	SS
37	11950; 12000; 13000; 13100; 13300; 13800-15200; 15500-16850; 16900-17600	SS
38	11300-11450; 11750-12700; 14400-15900; 16000	SS
39	15950-17900	SS
40	19000-20700	HC
	04900; 04950	CS
41	20500; 20550; 20750-22250	HC
42	21500; 21550; 22200-22800	HC
43	22550; 22600; 22850-23200; 23400; 23450	HC
44	23150-23250; 23400-24000	HC

KEY

ST = Strait of Juan de Fuca Geoduck Region

SJ = San Juan Islands Geoduck Region

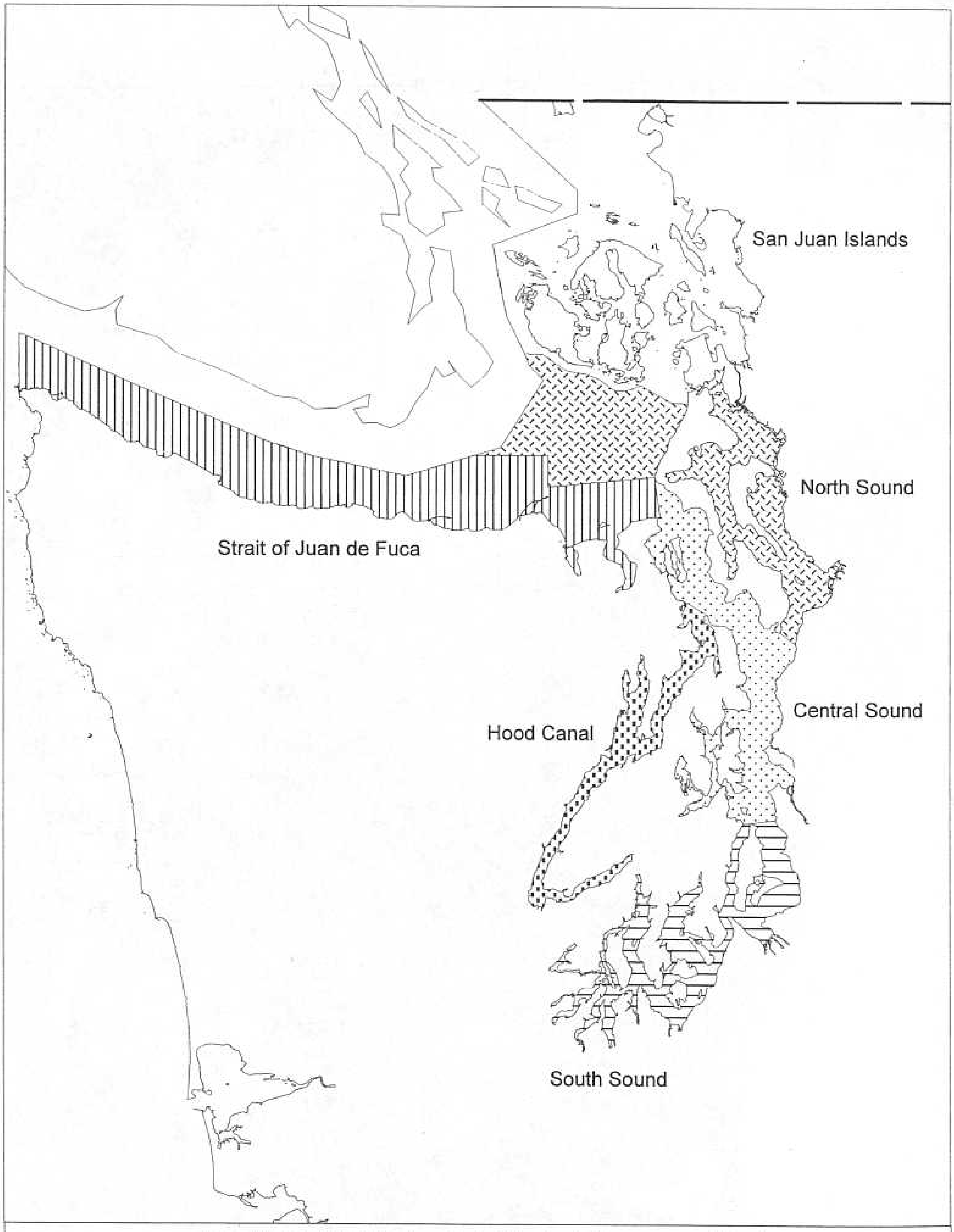
NS = North Sound Geoduck Region

CS = Central Sound Geoduck Region

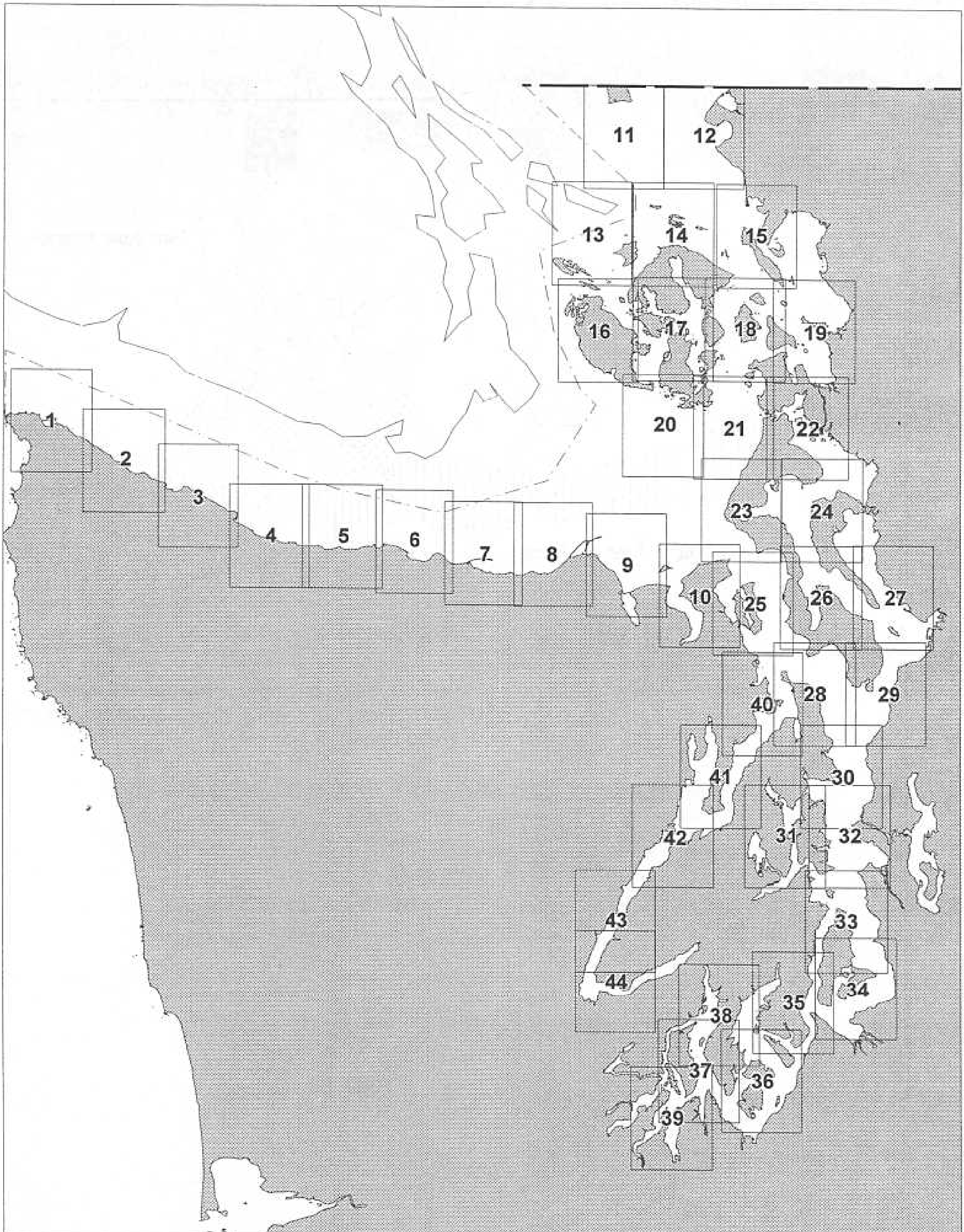
SS = South Sound Geoduck Region

HC = Hood Canal Geoduck Region

NB = No known geoduck beds within the area covered by the figure



Area Map I. Washington State Geoduck Management Regions



Area Map II. Figure Index Map

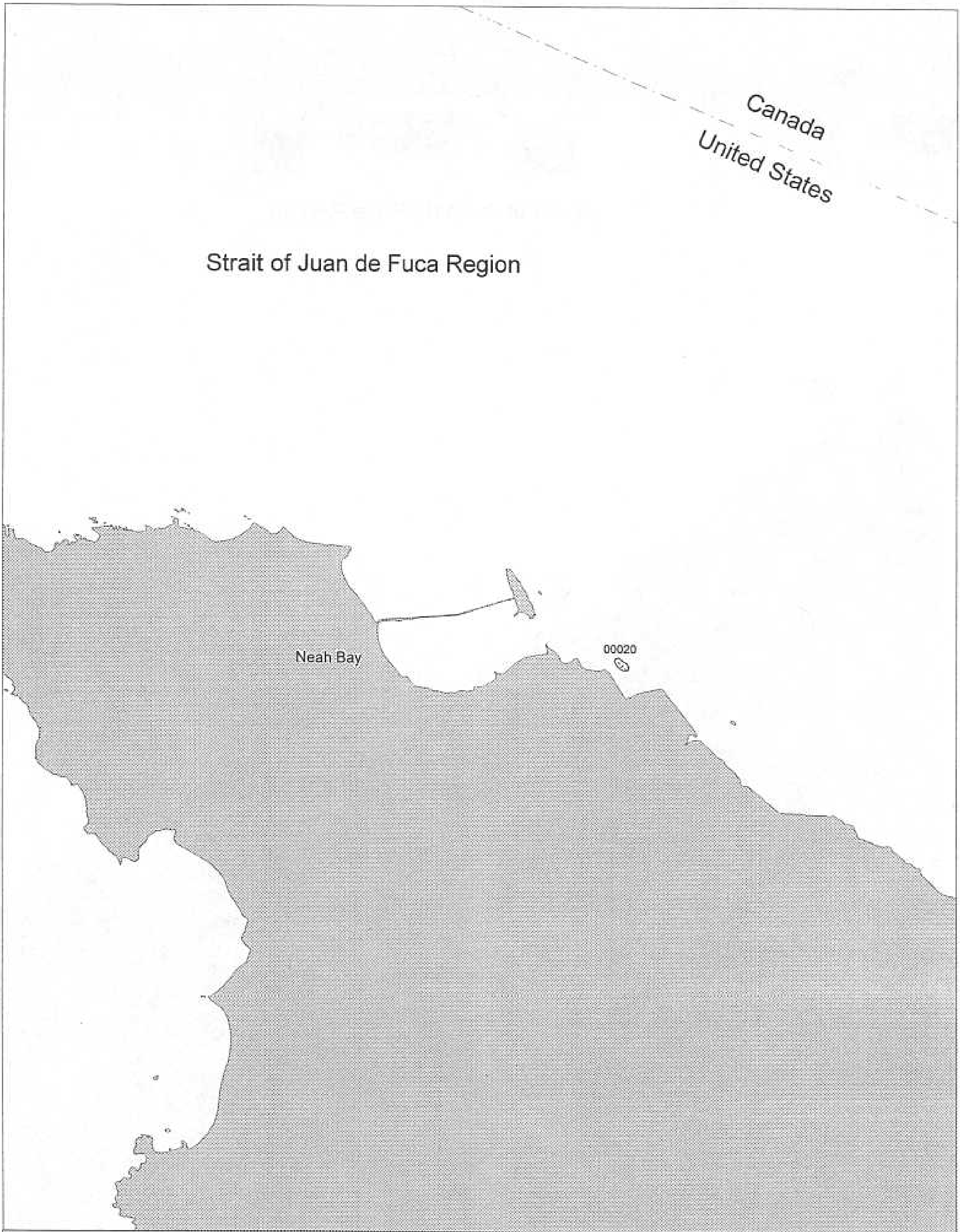
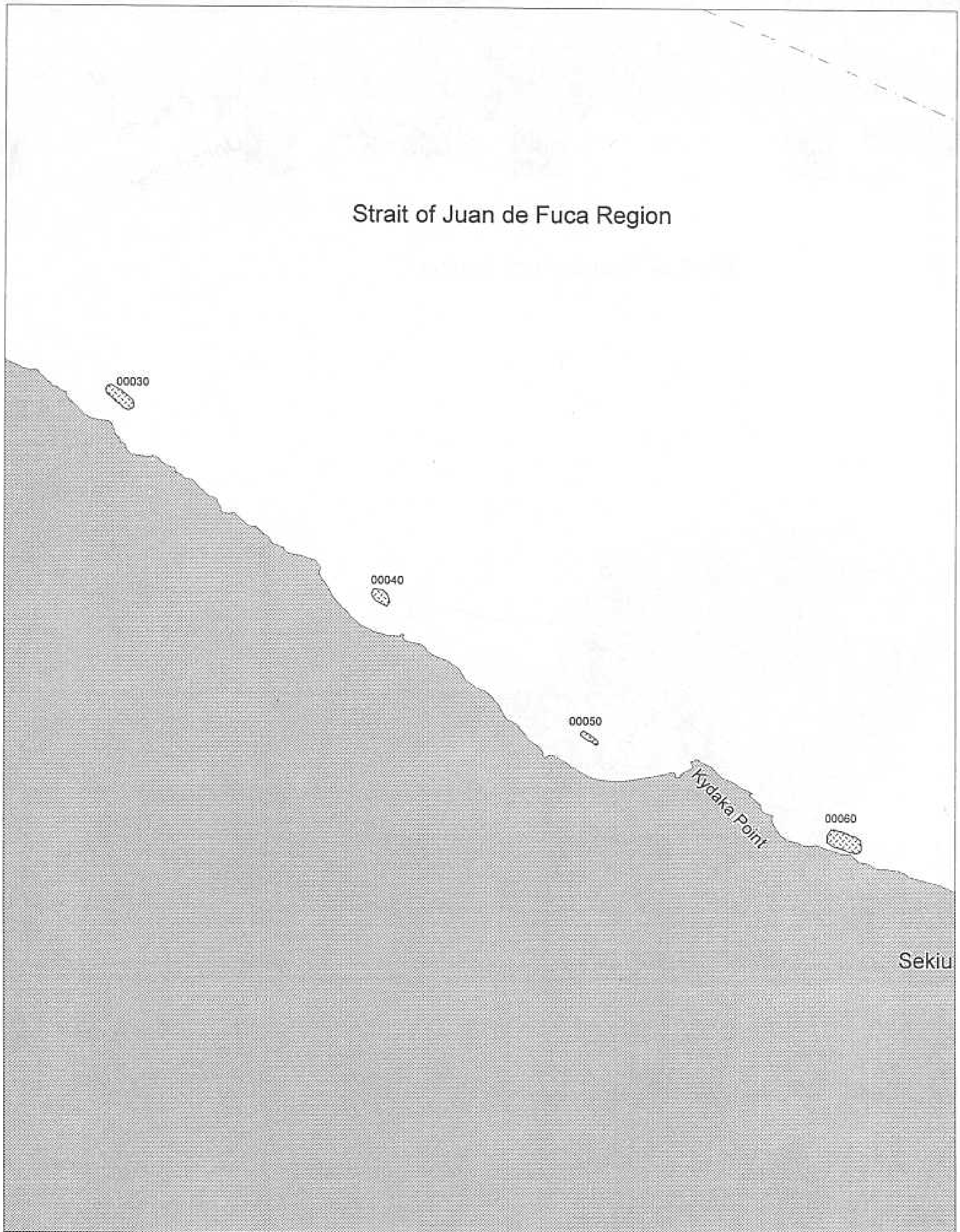


Figure 1. Vicinity Map. To be used as a visual aid only. Tracts may not be to exact proportion or scale.



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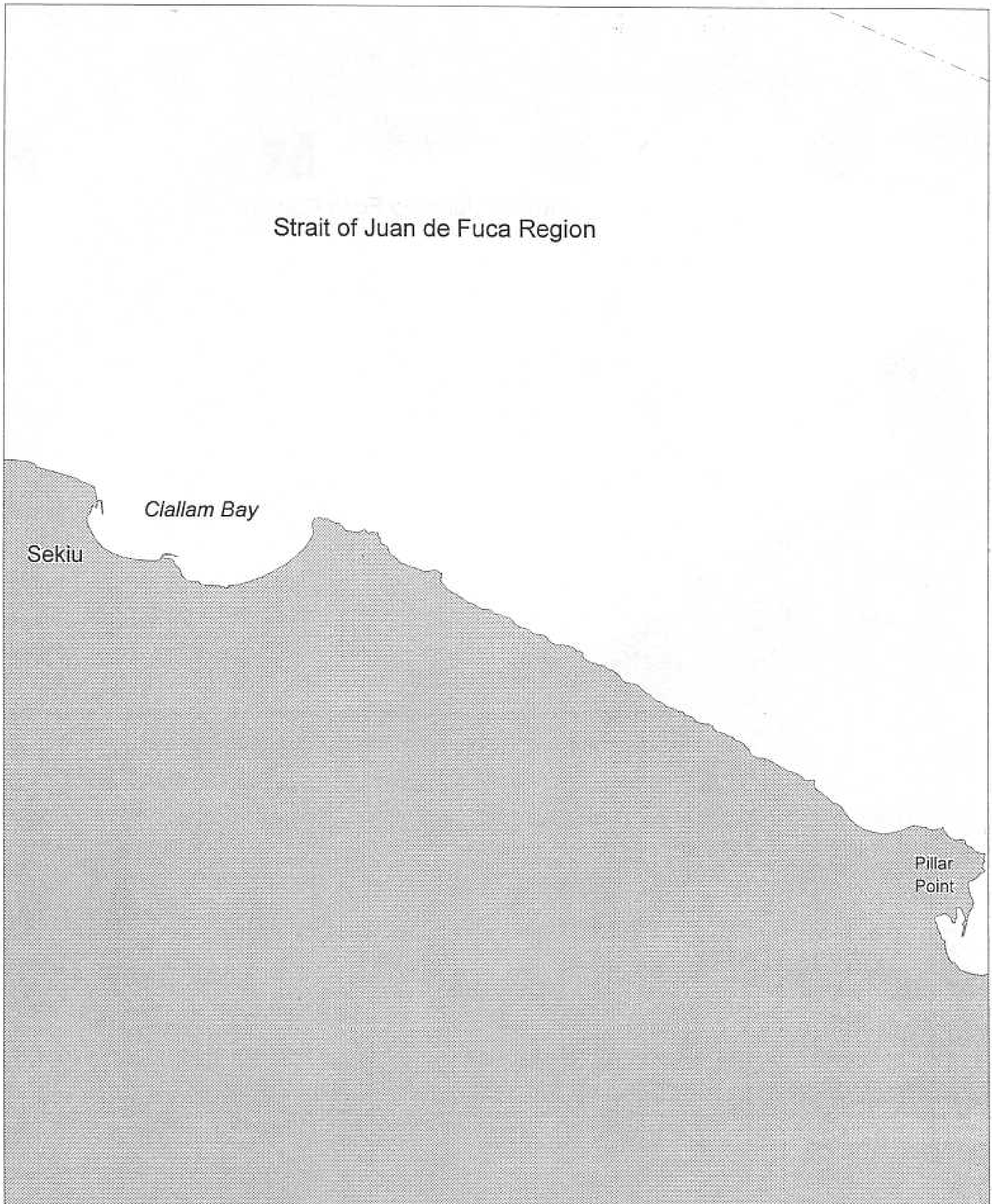

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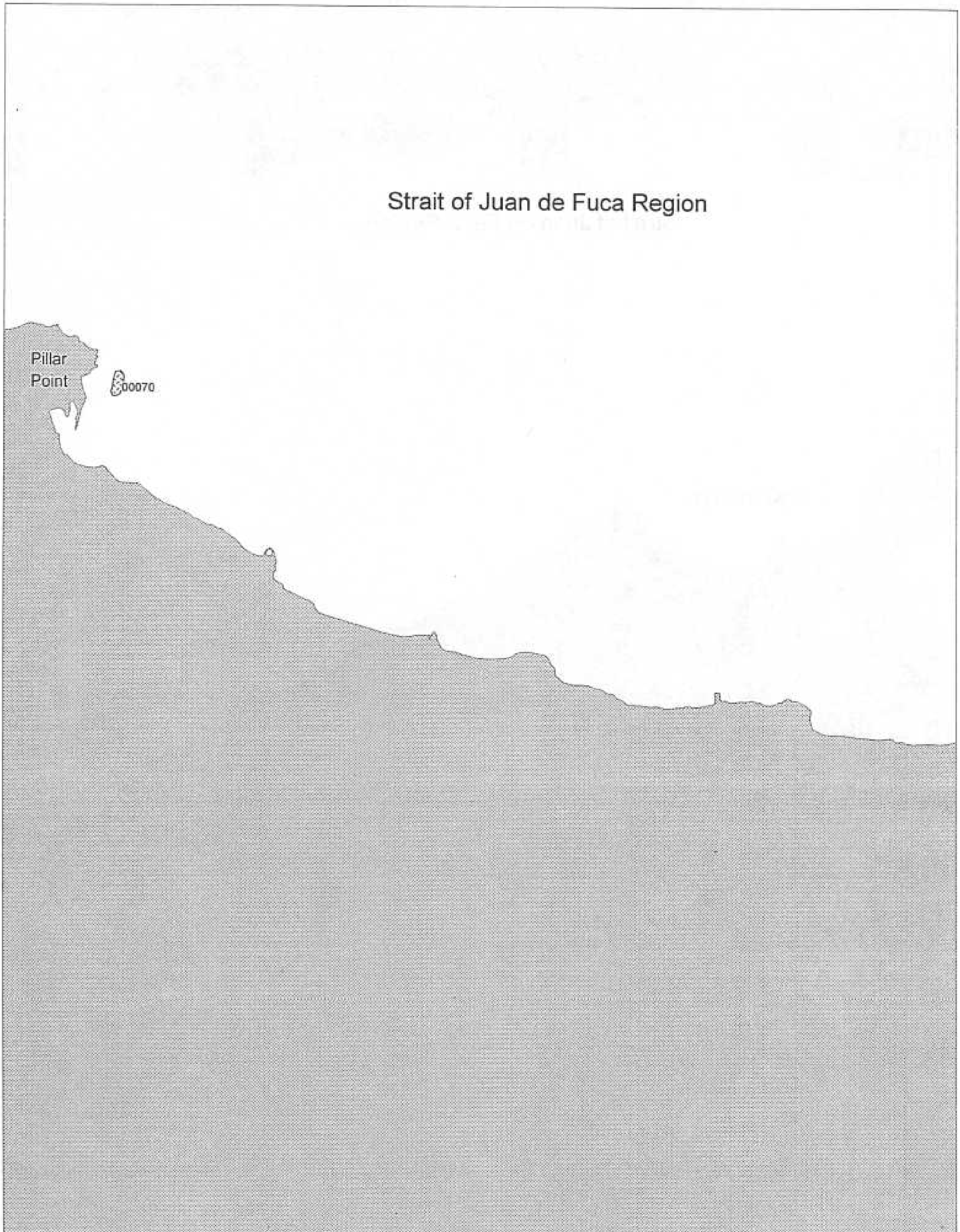

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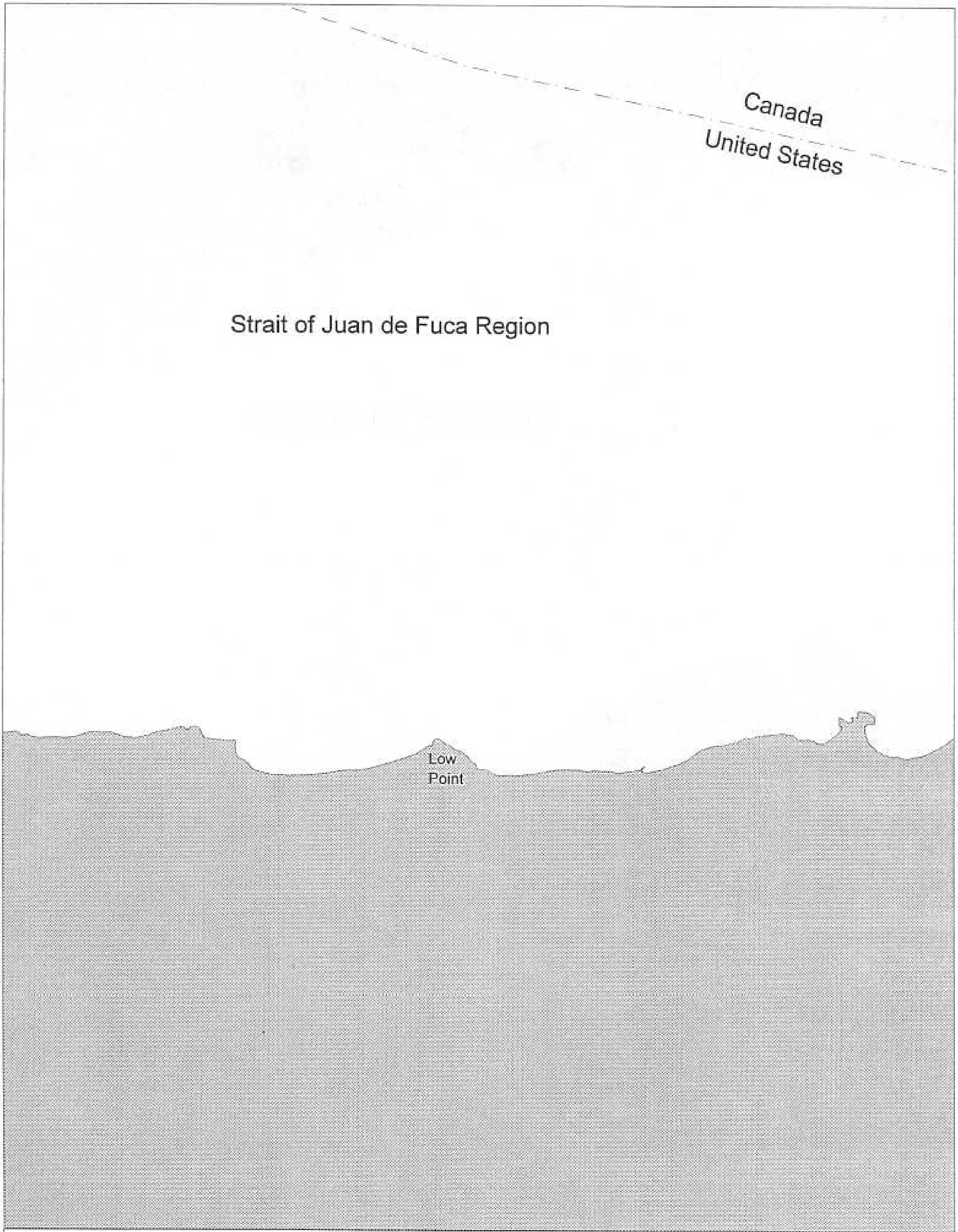

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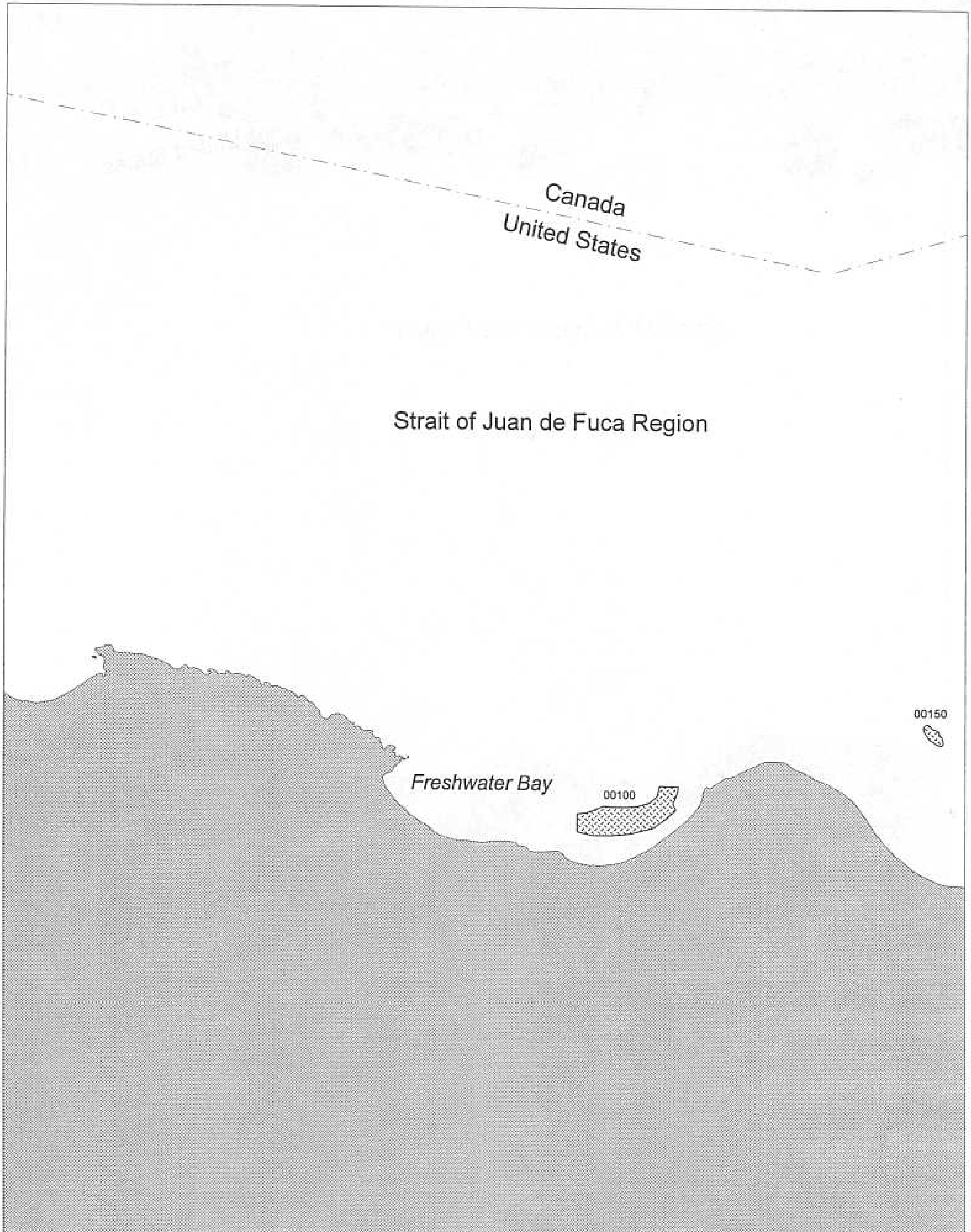

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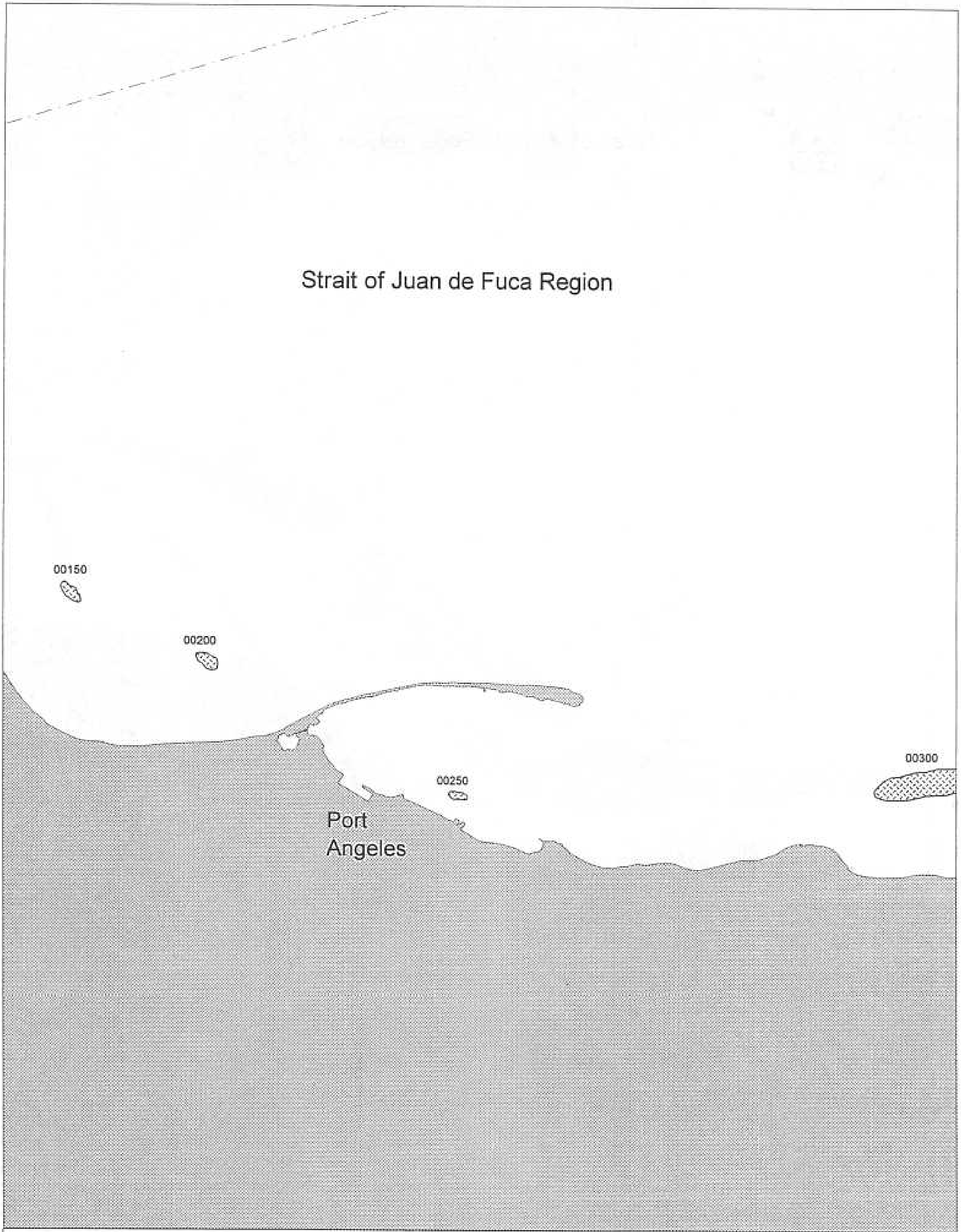

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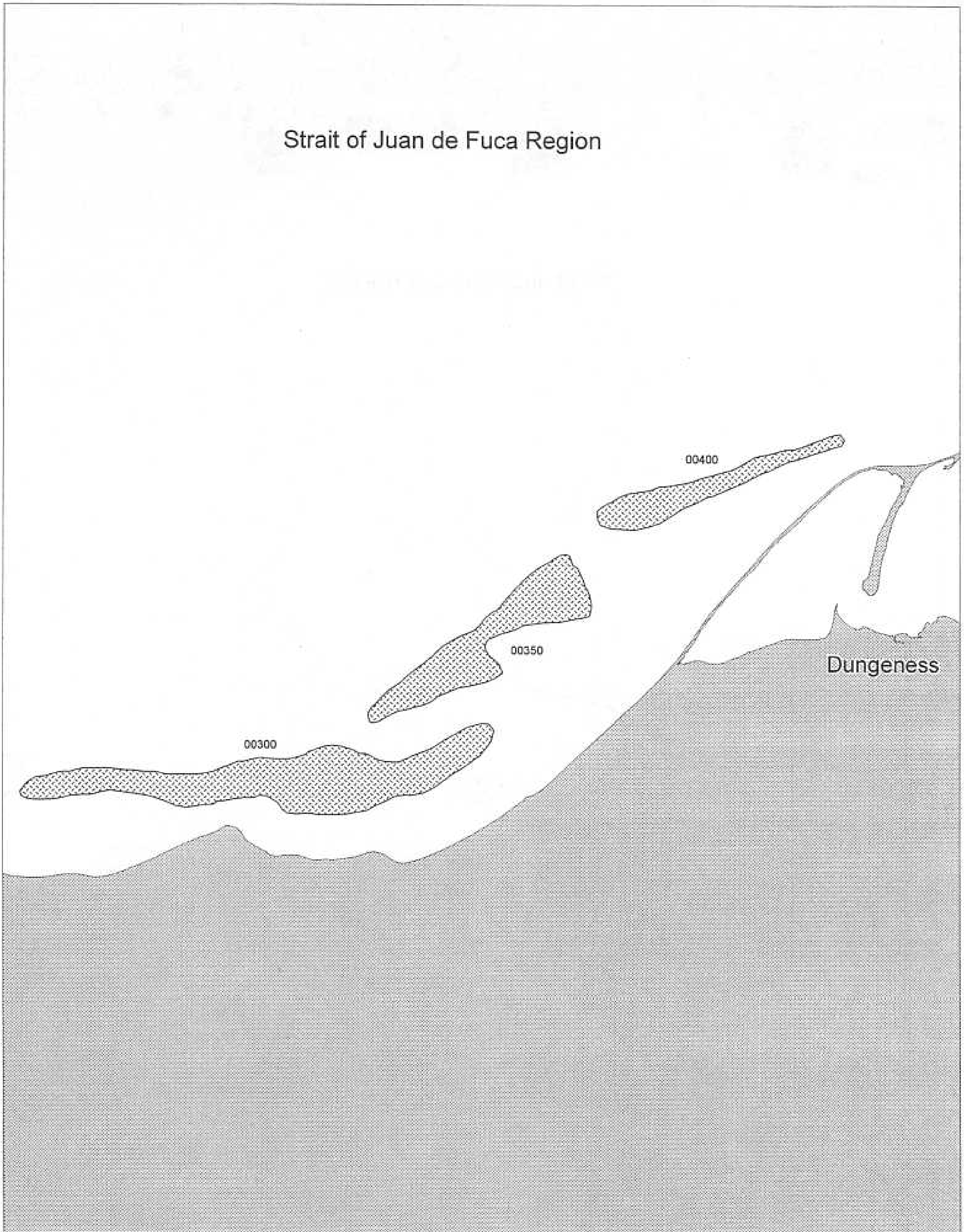

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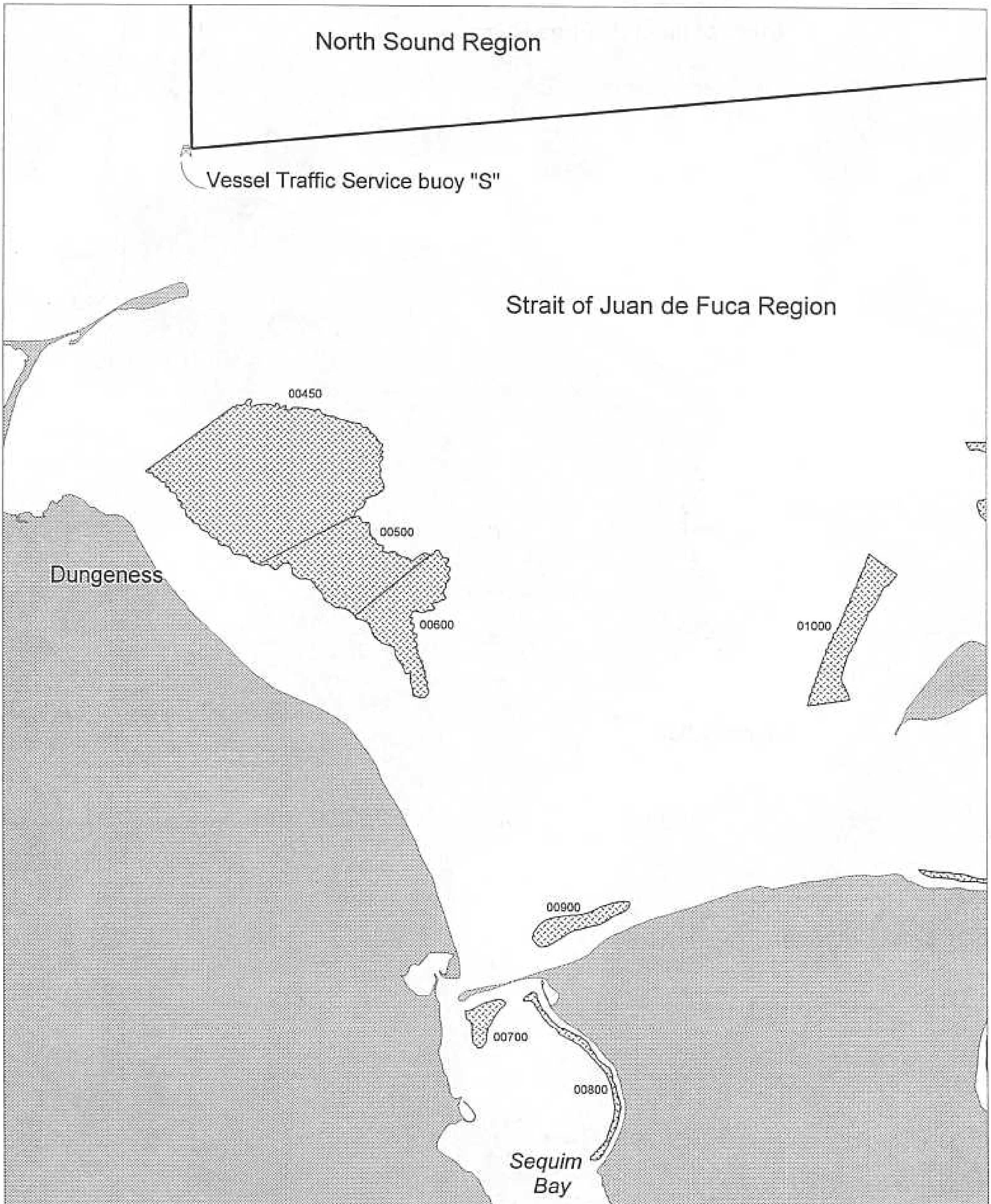

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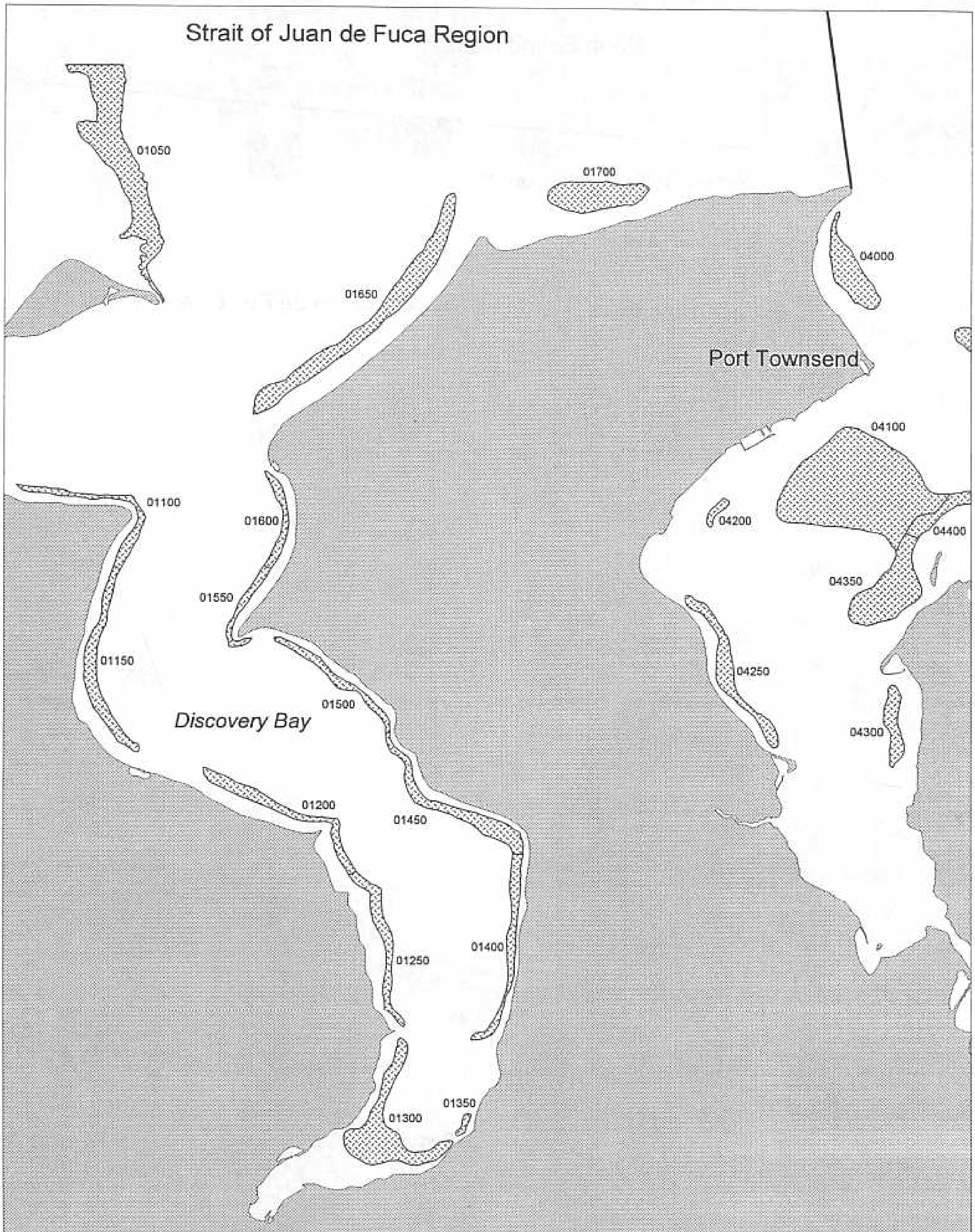

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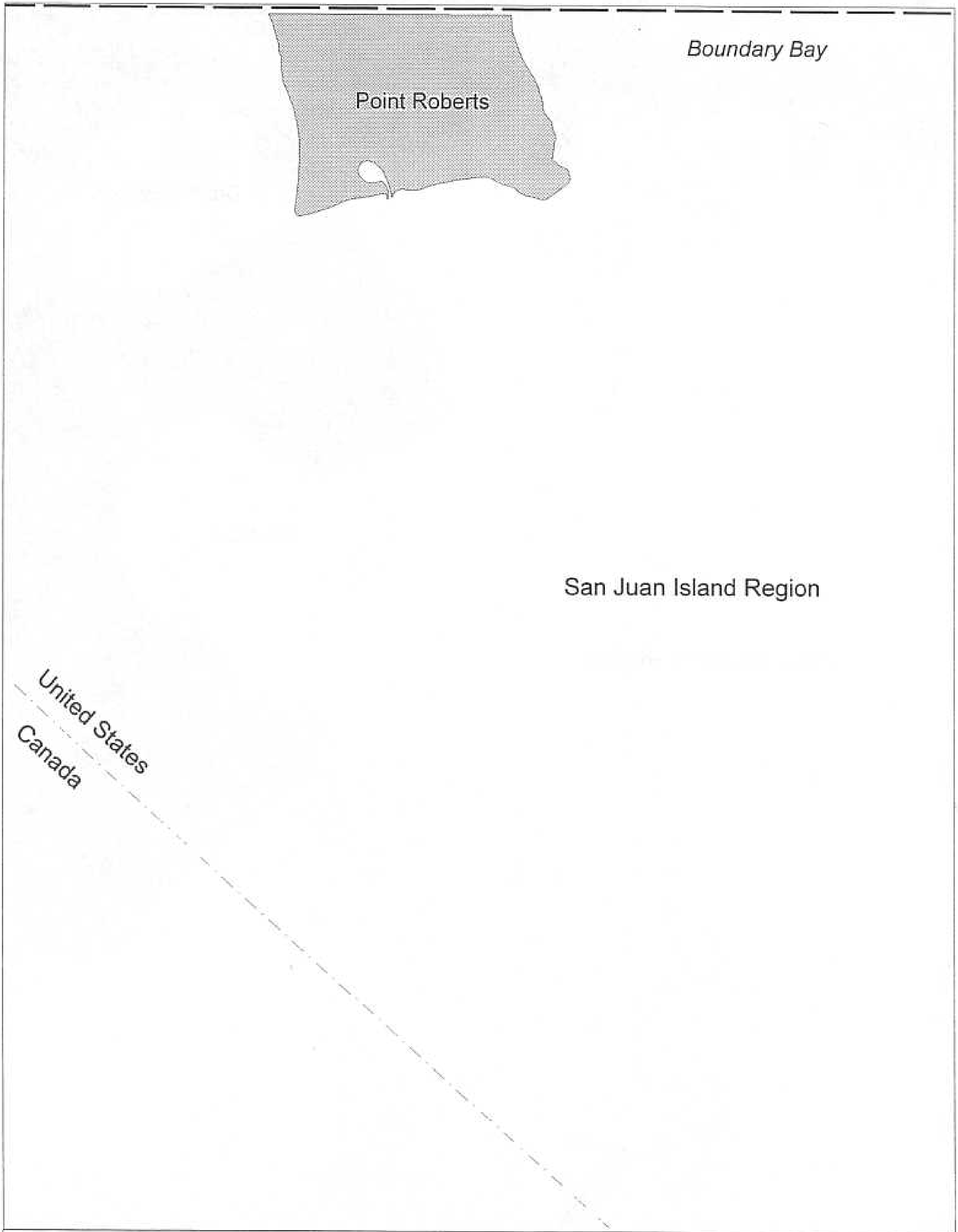

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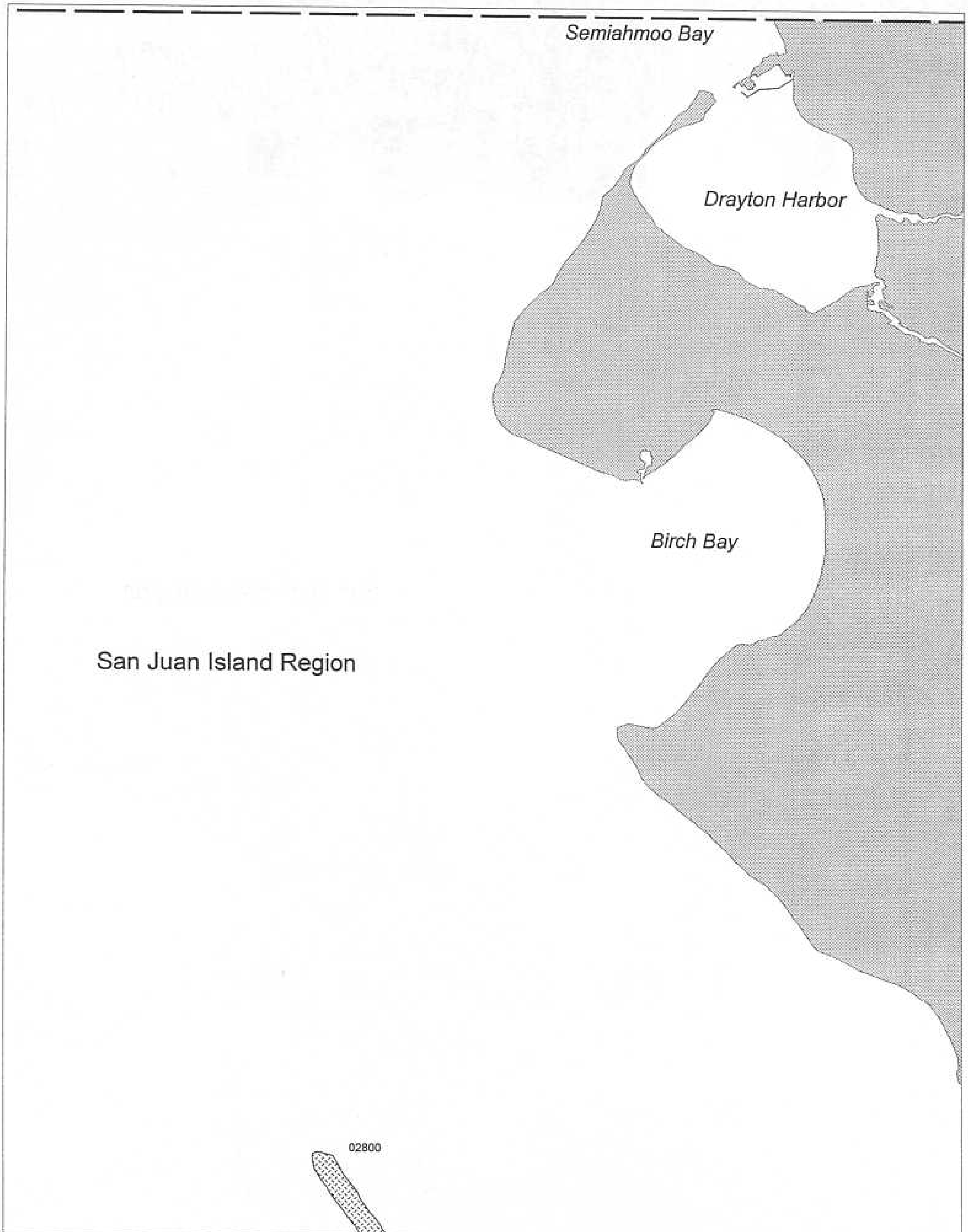

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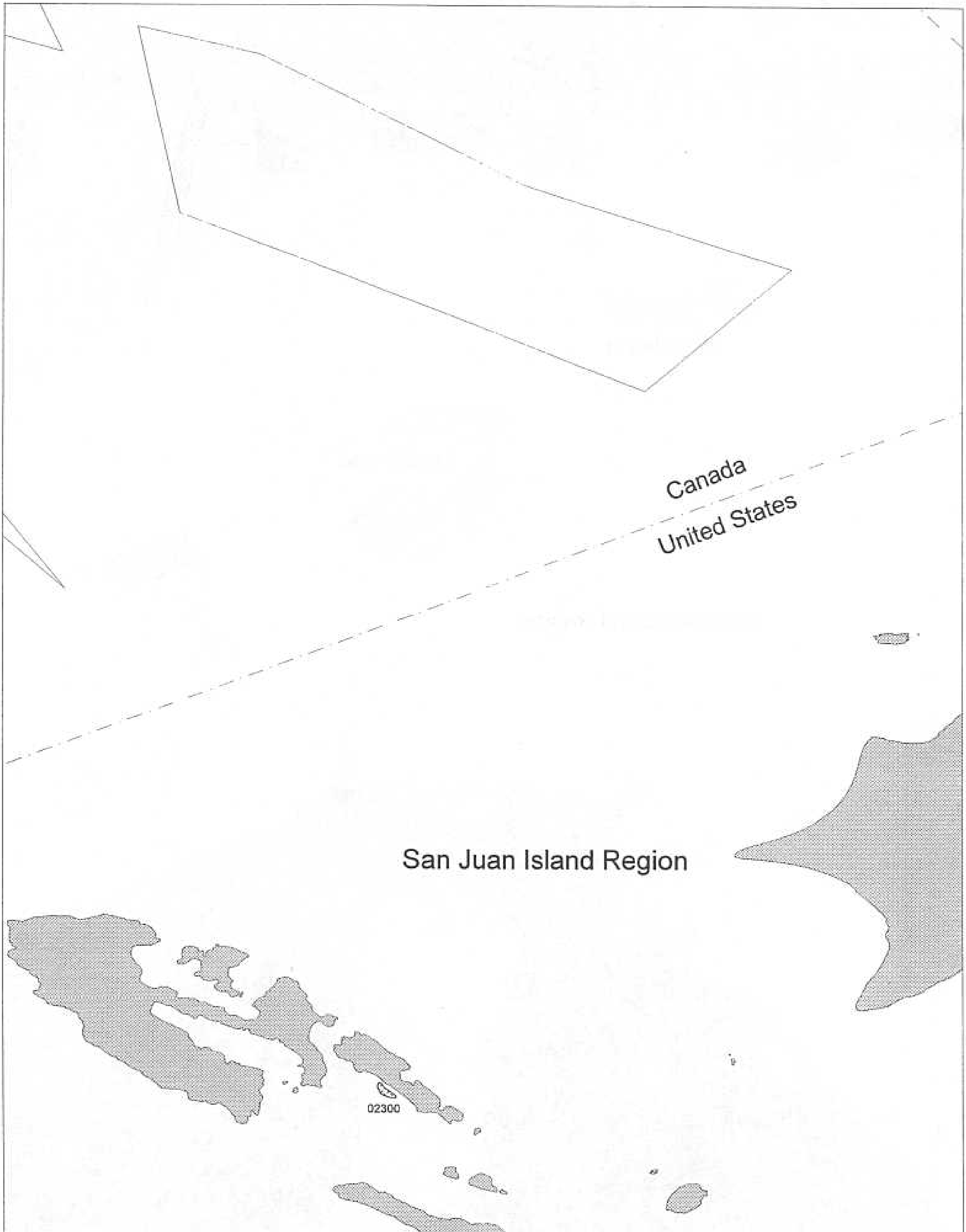

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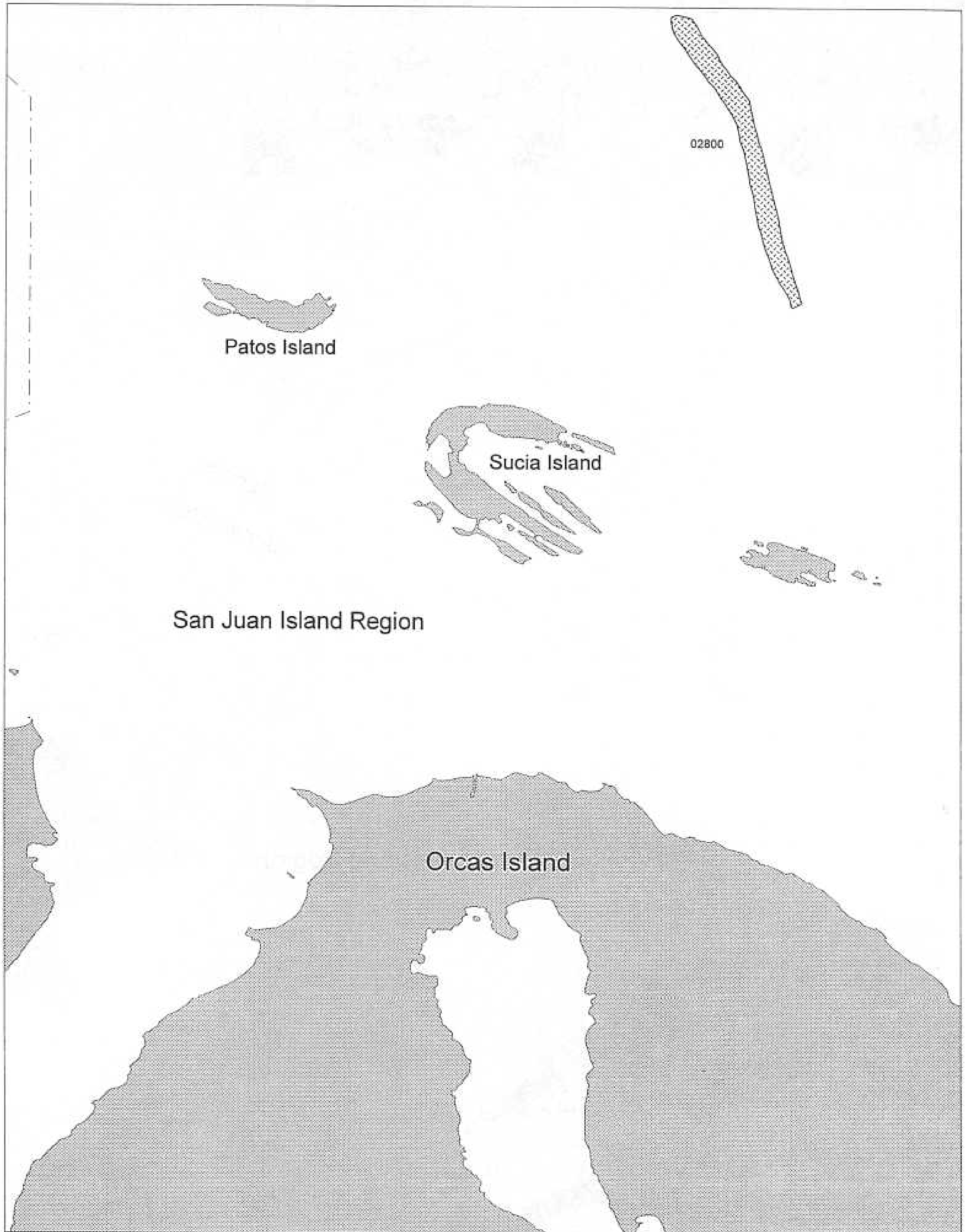

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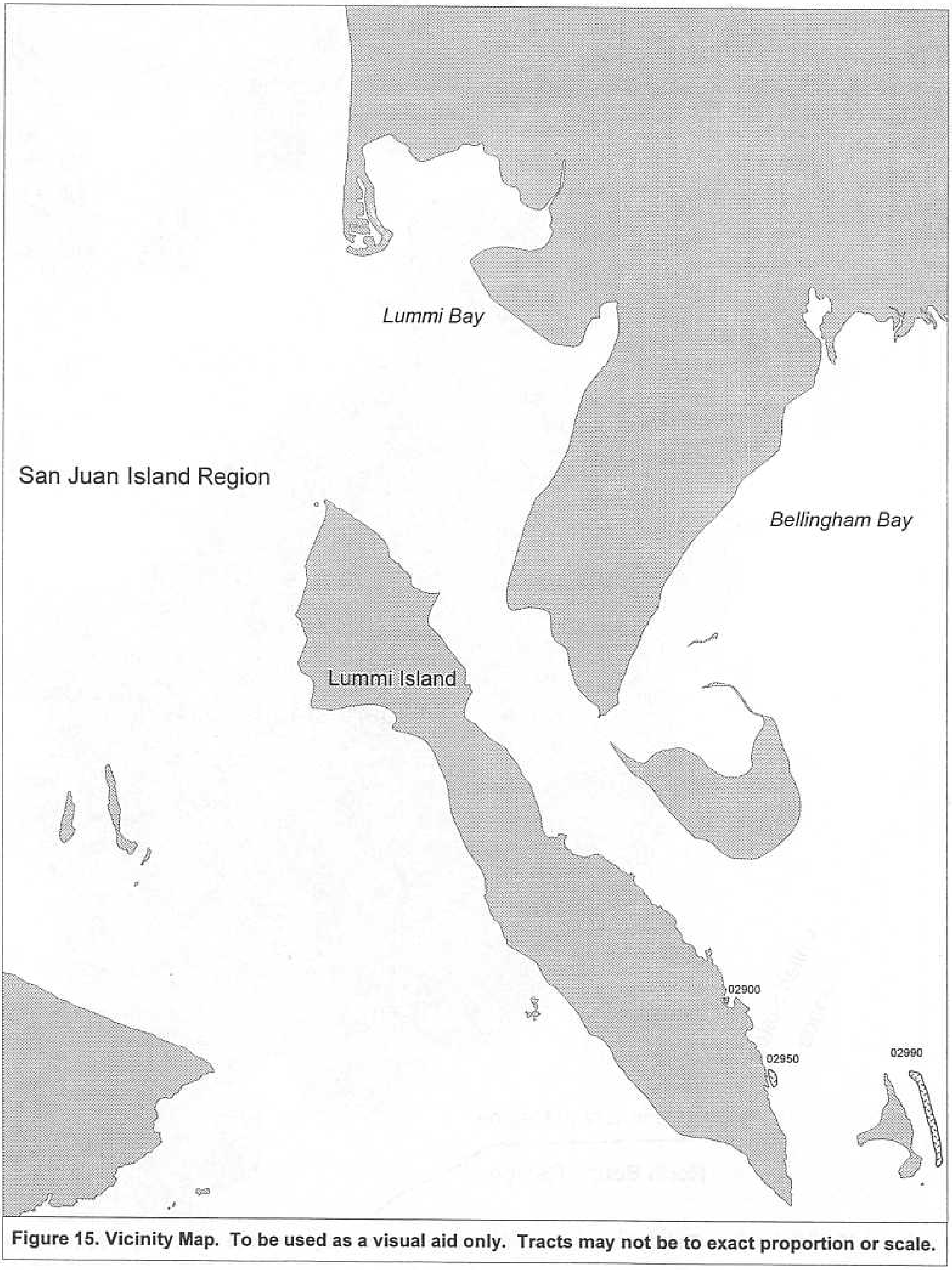

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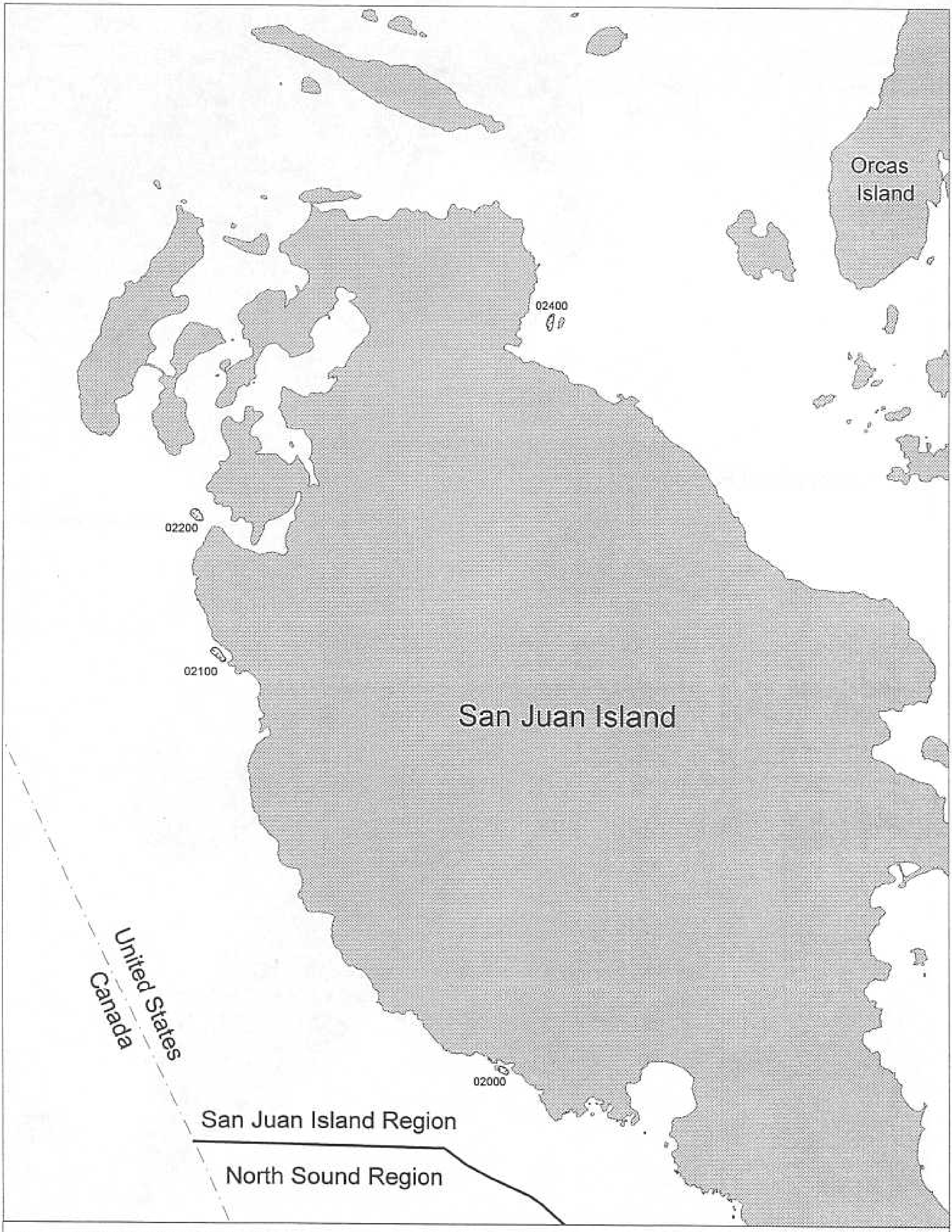

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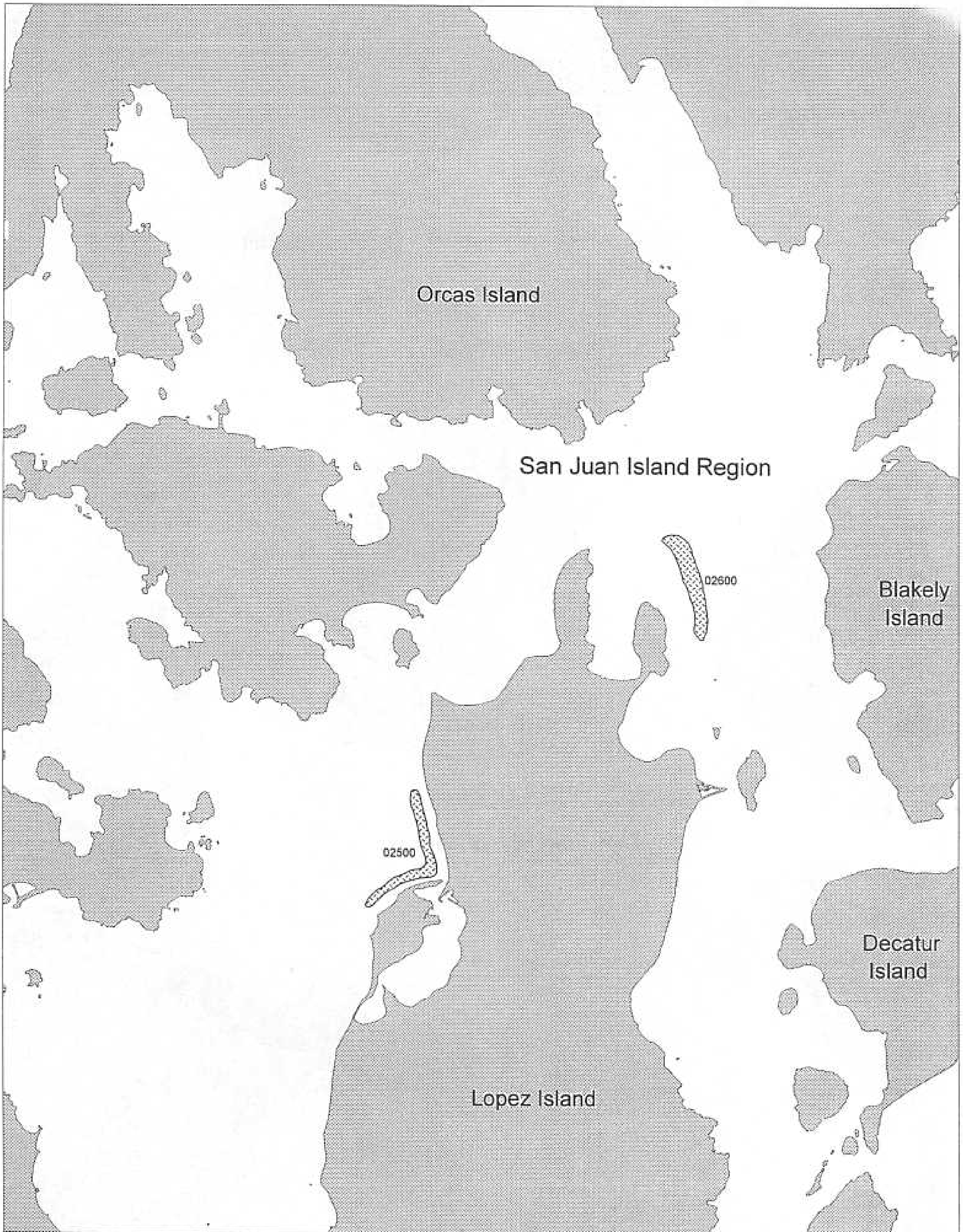

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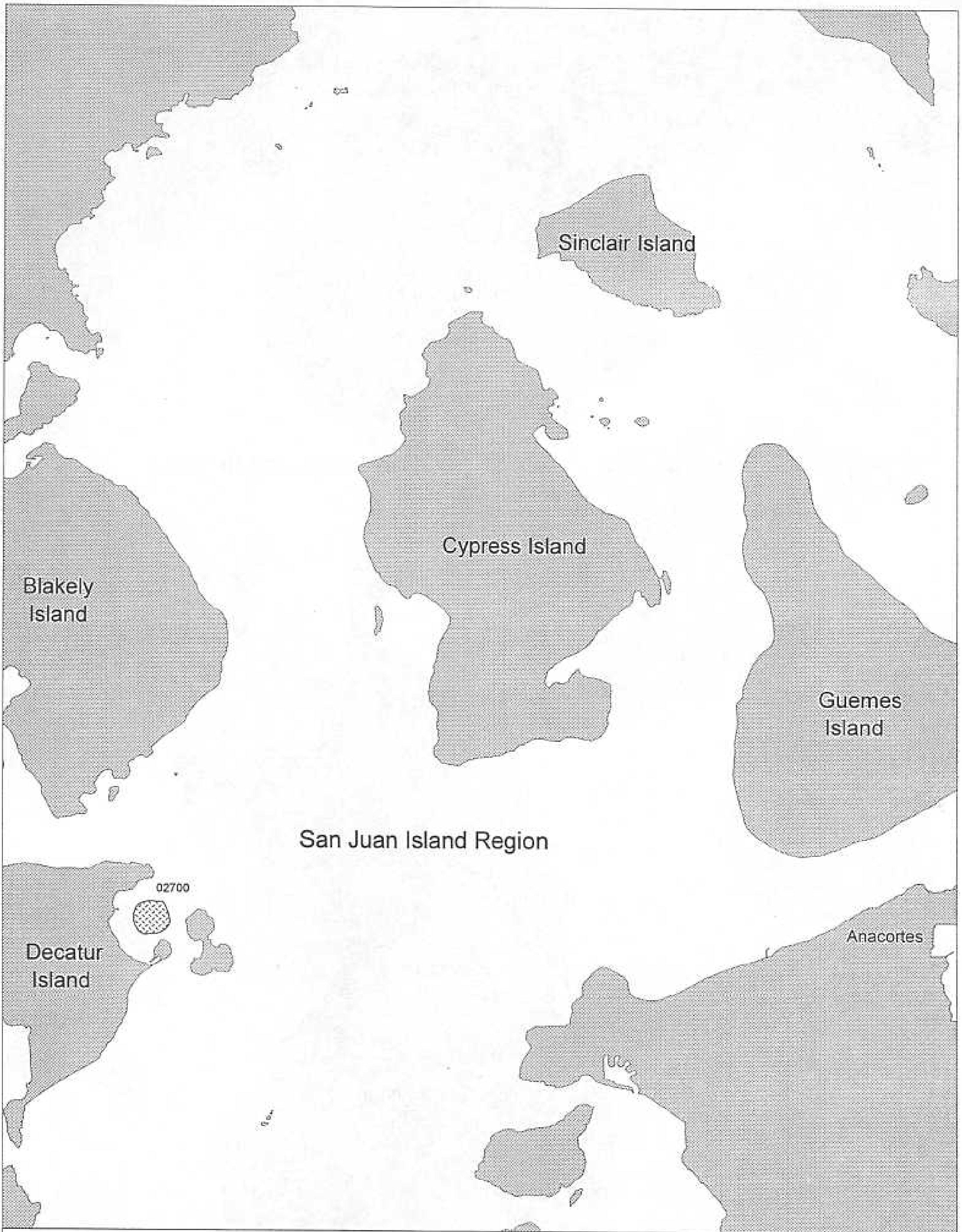

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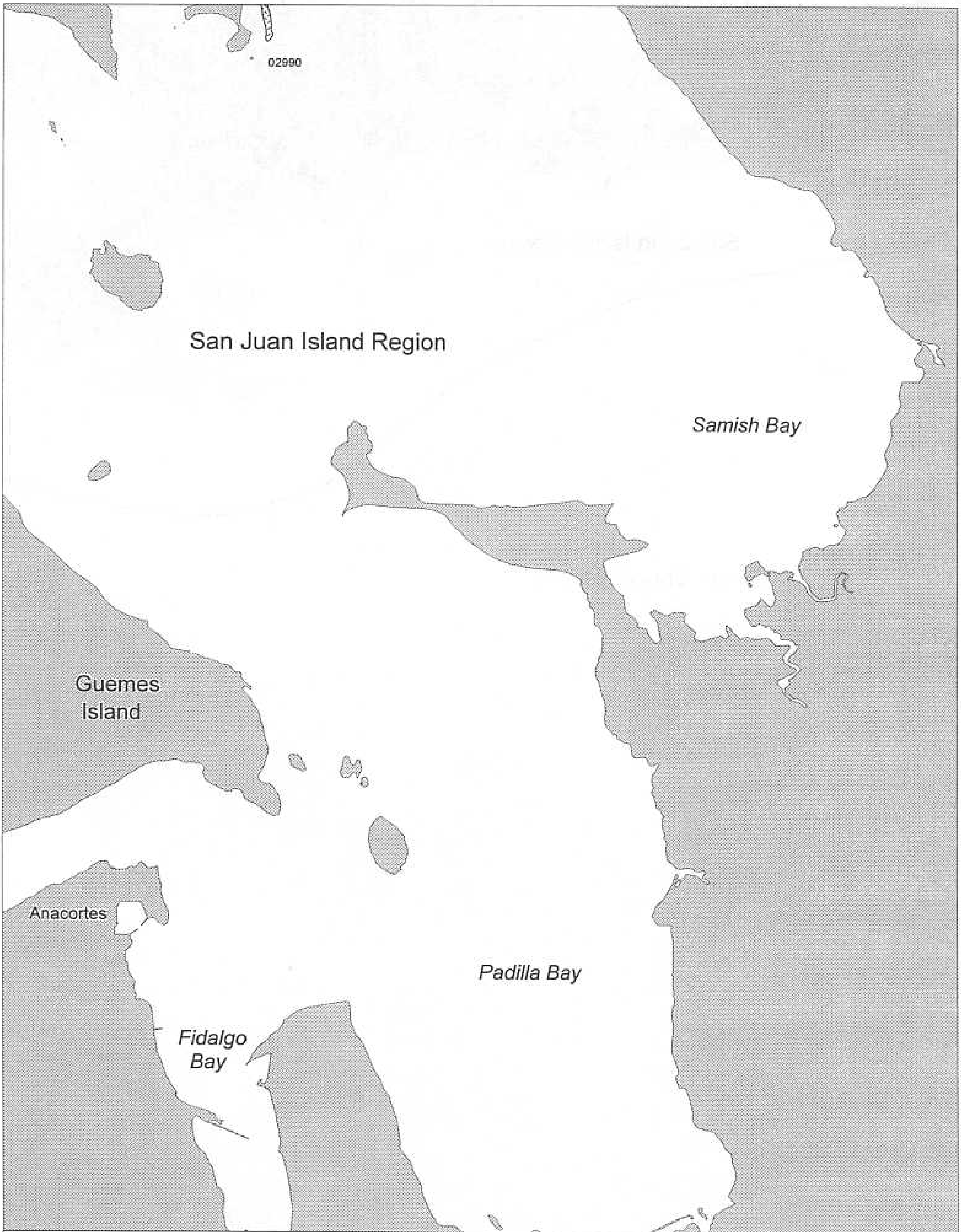

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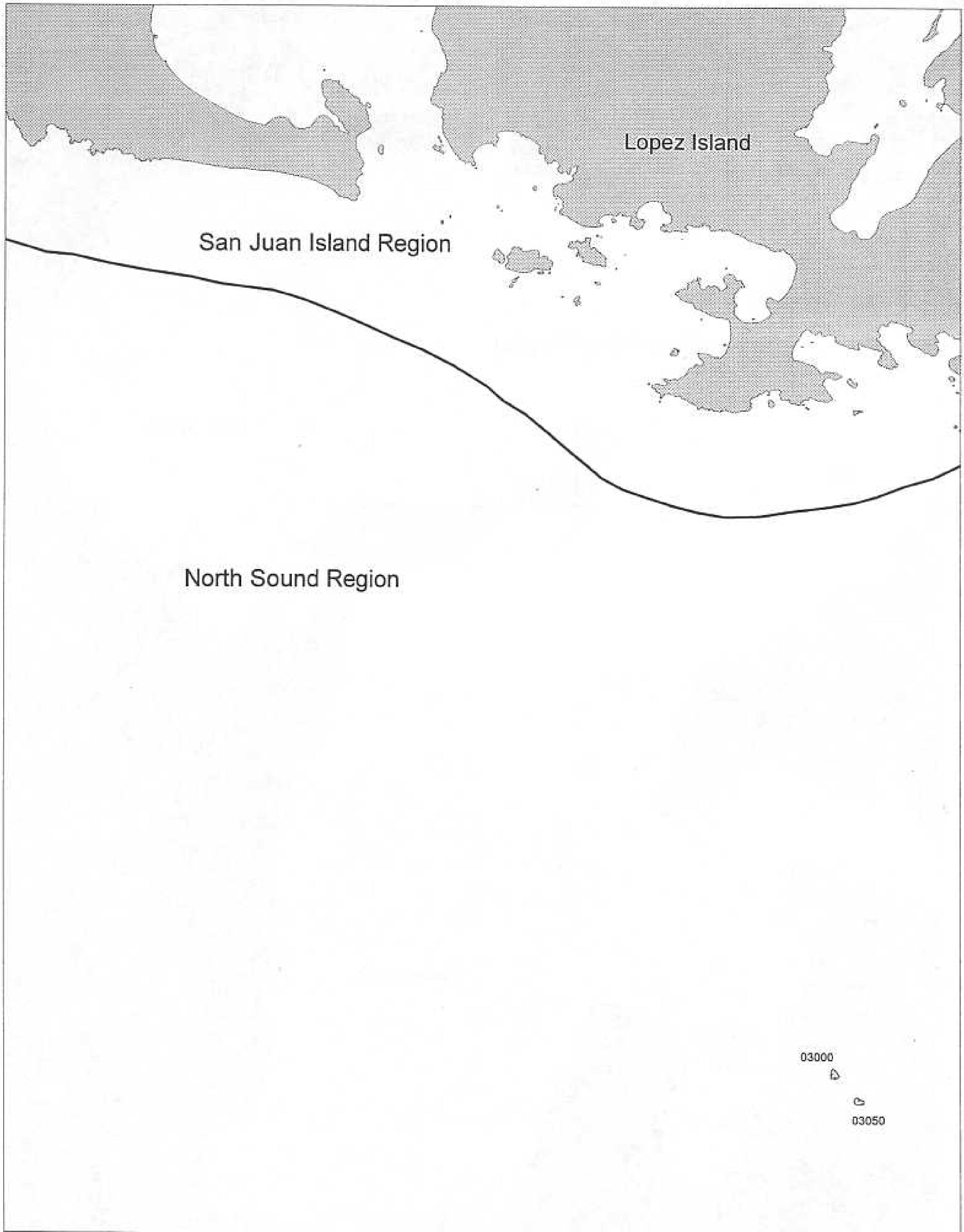

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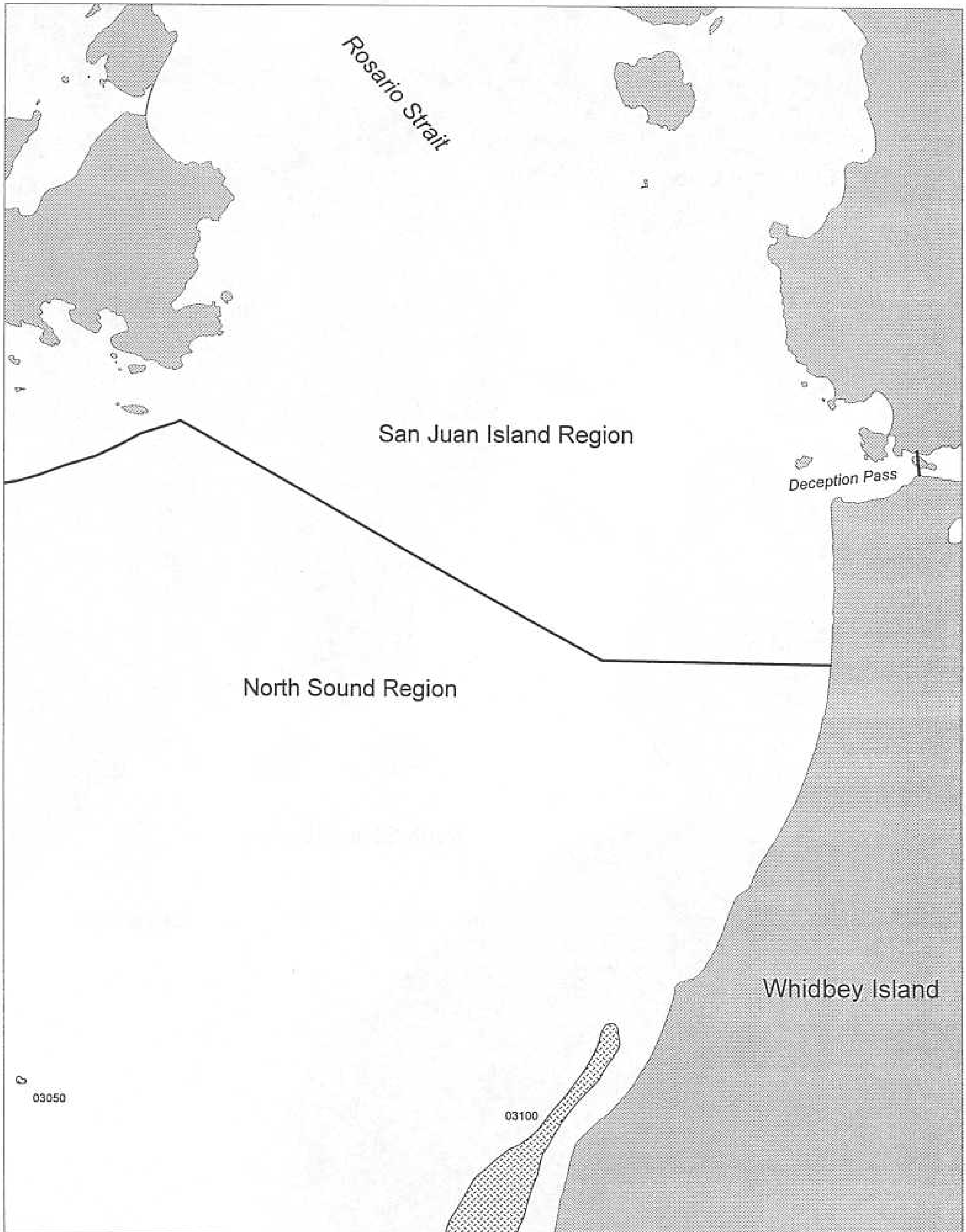

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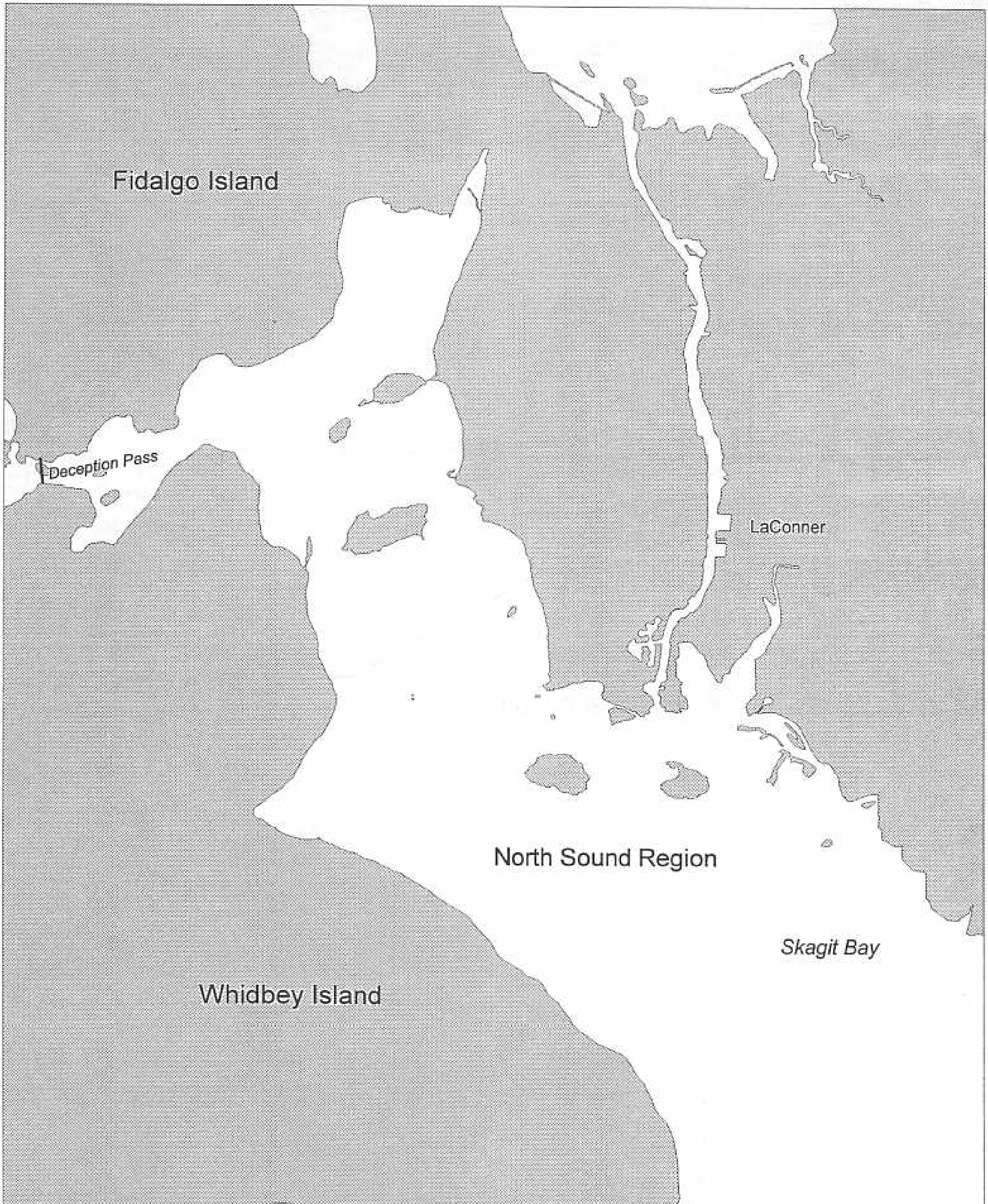

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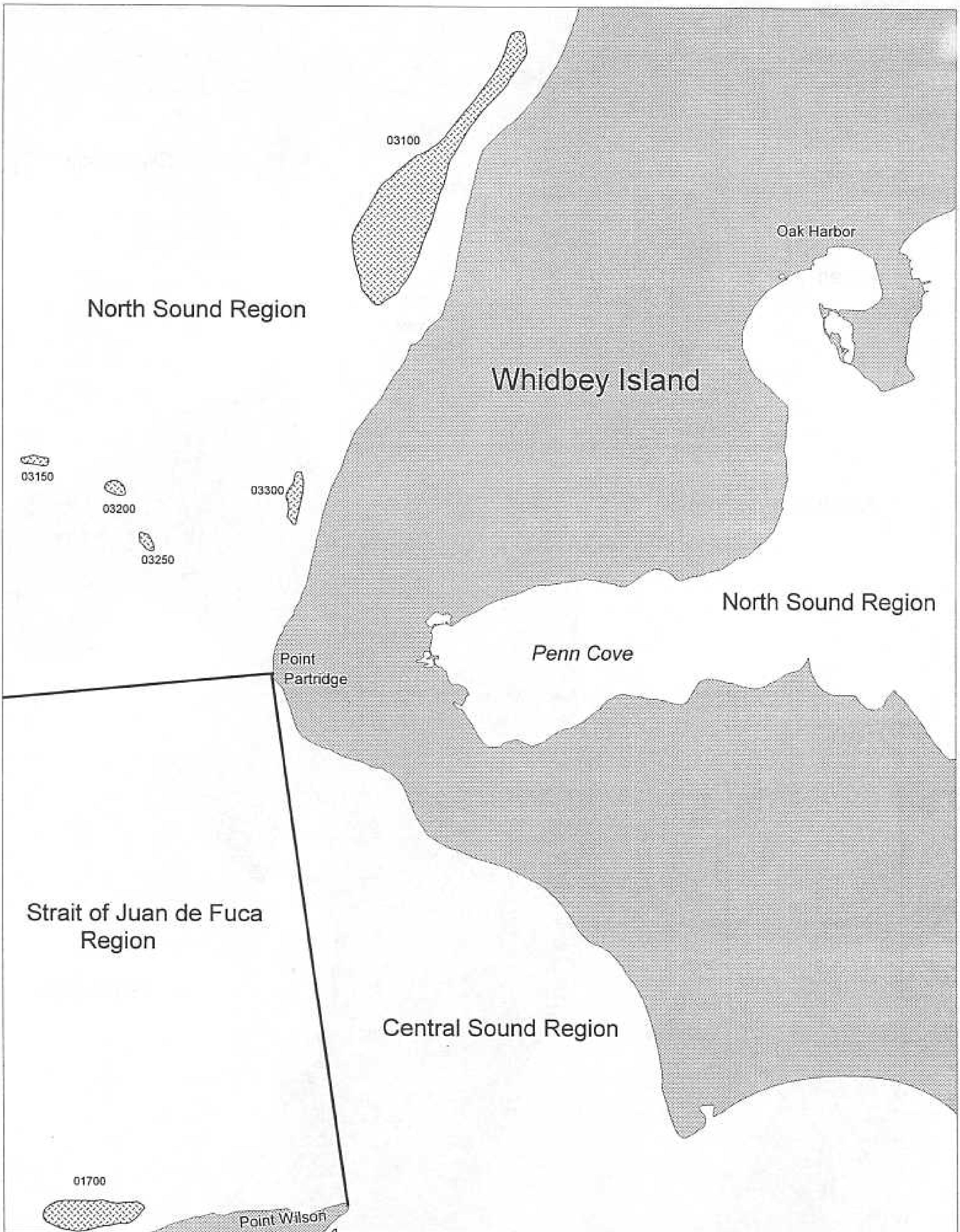

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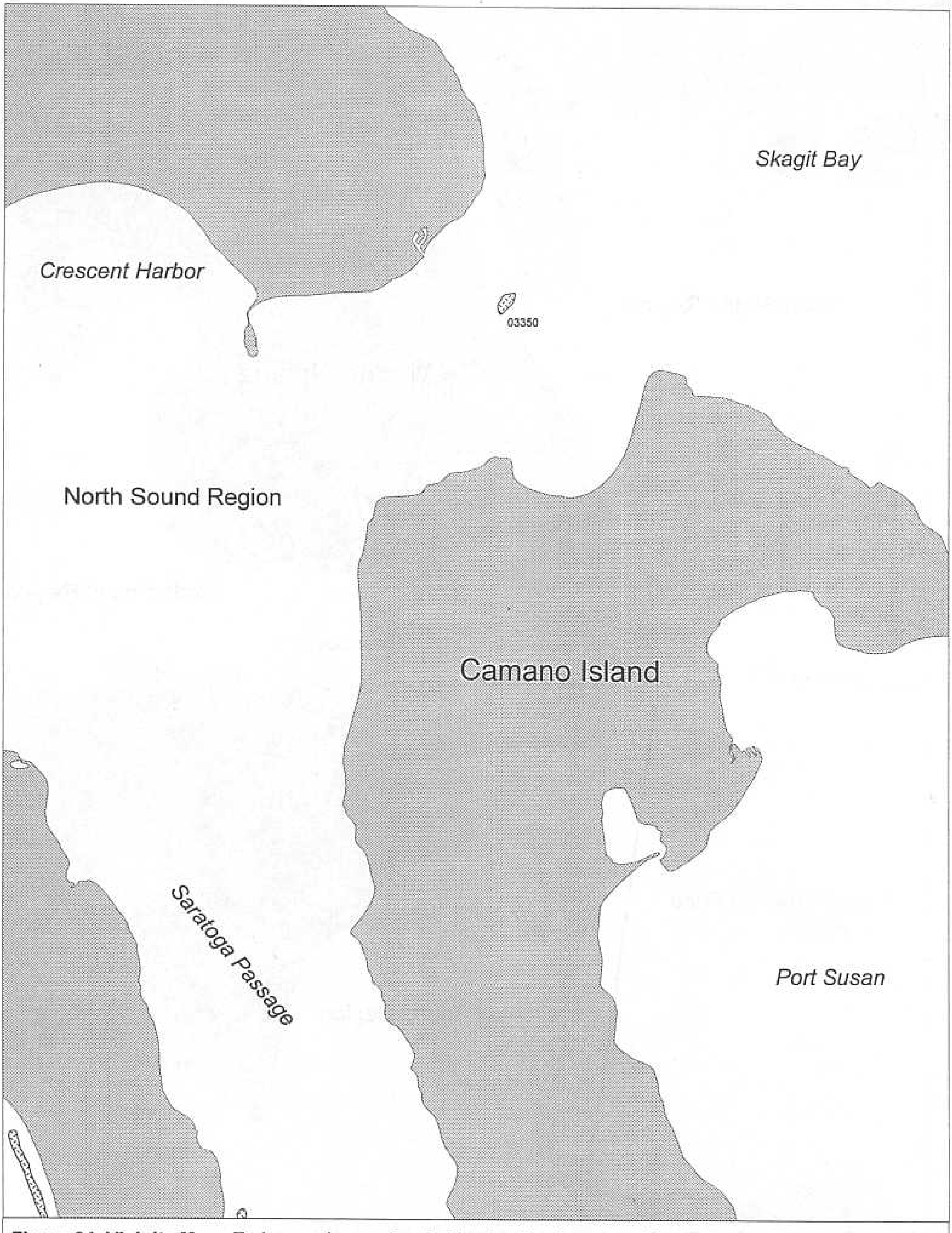

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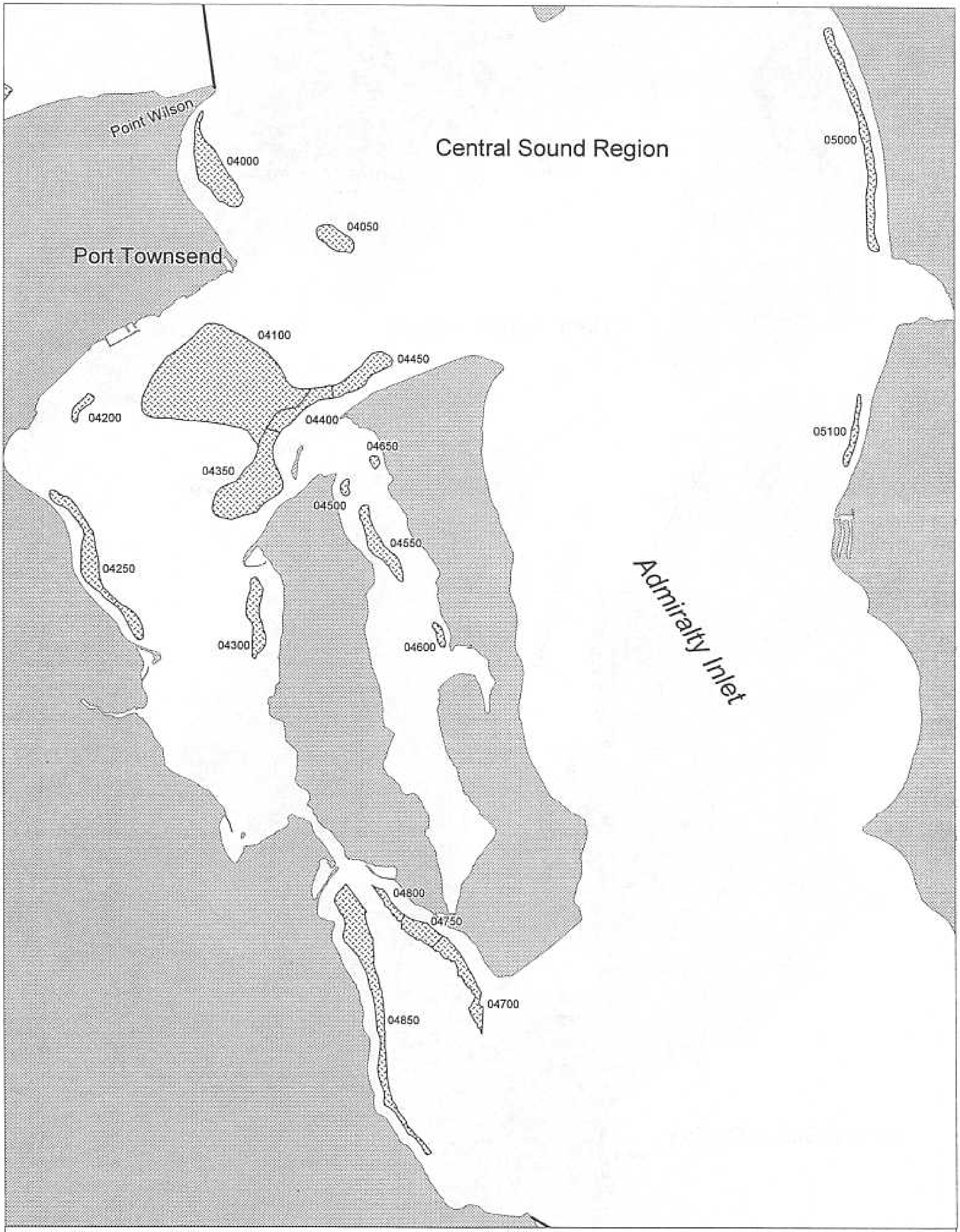

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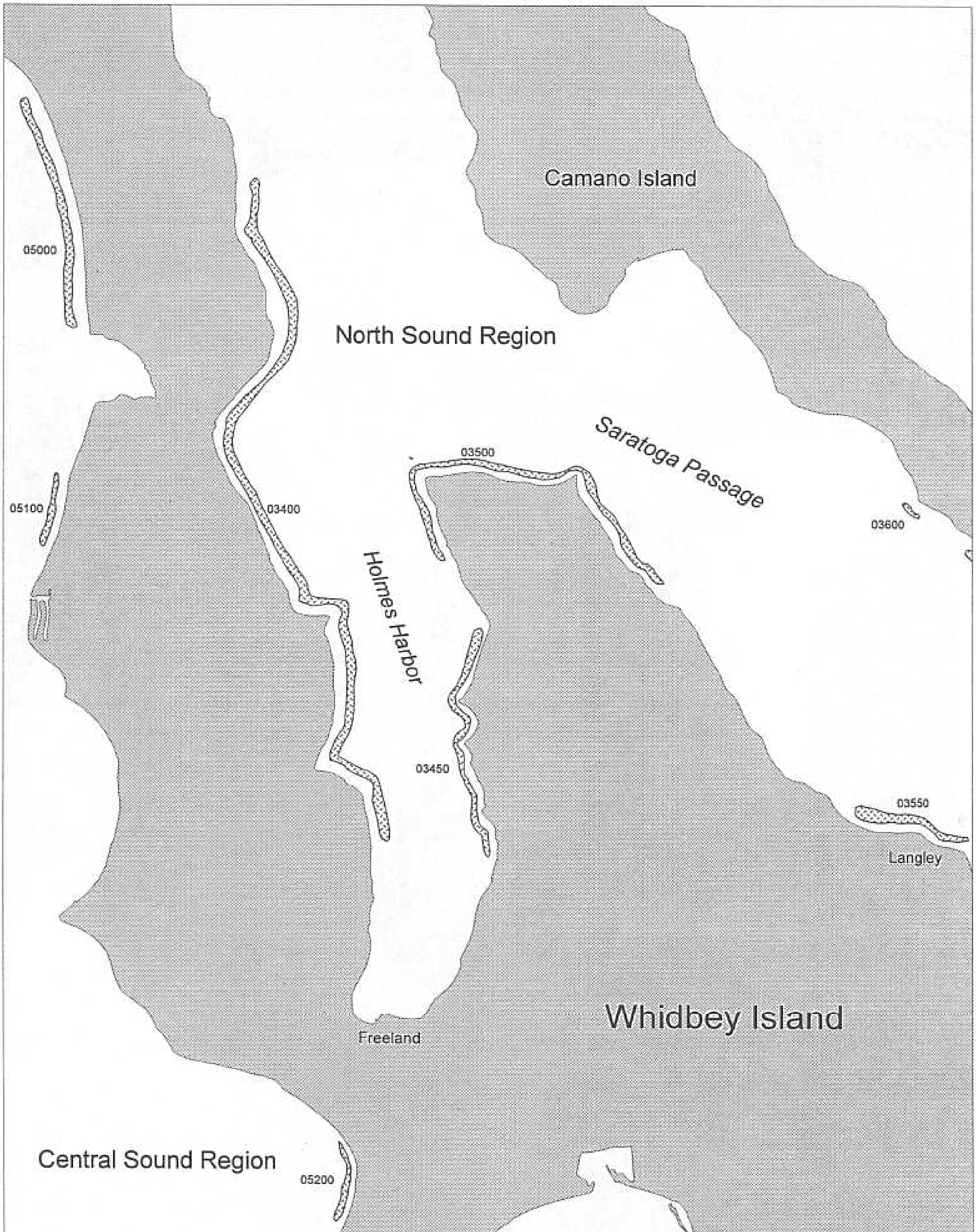

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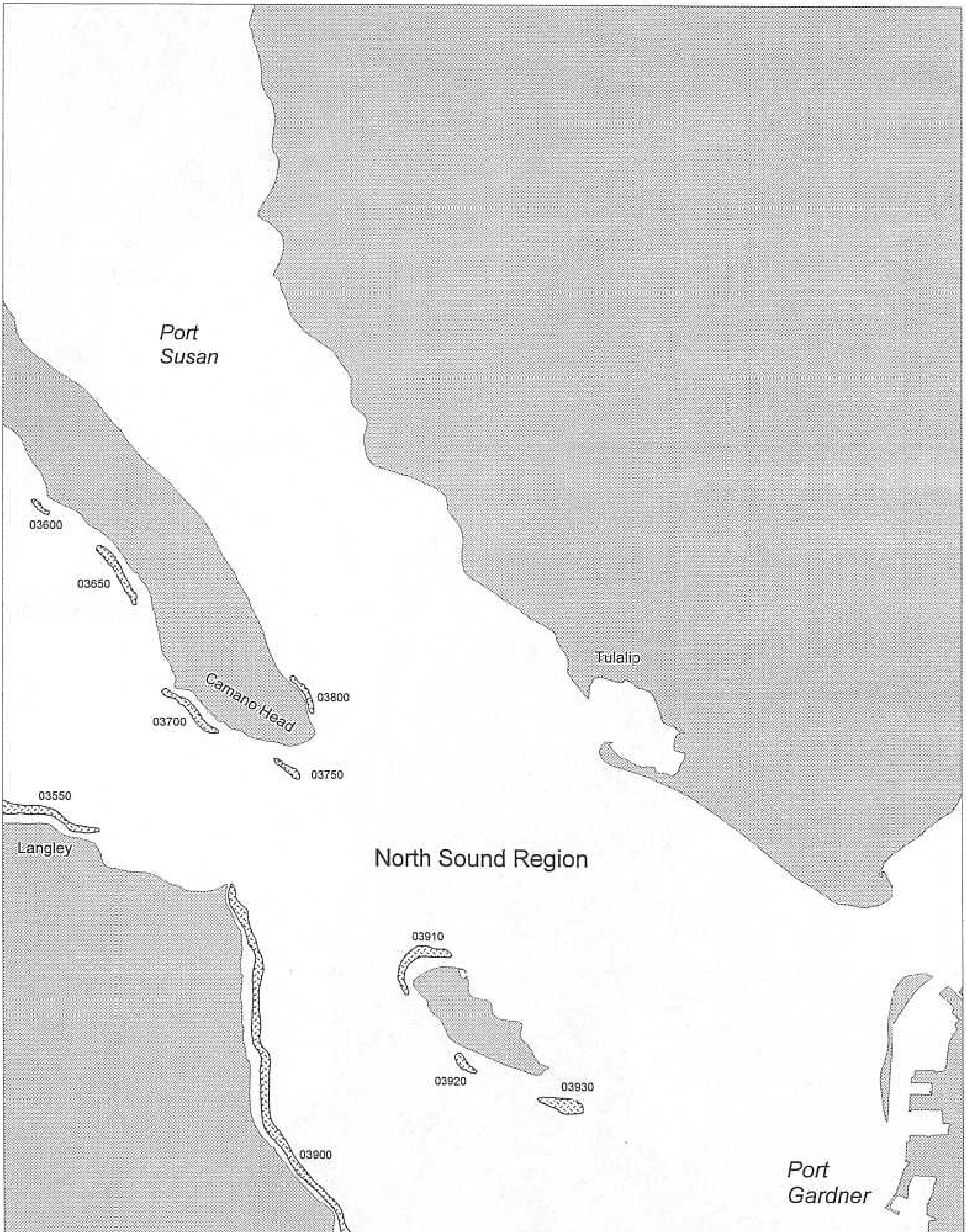

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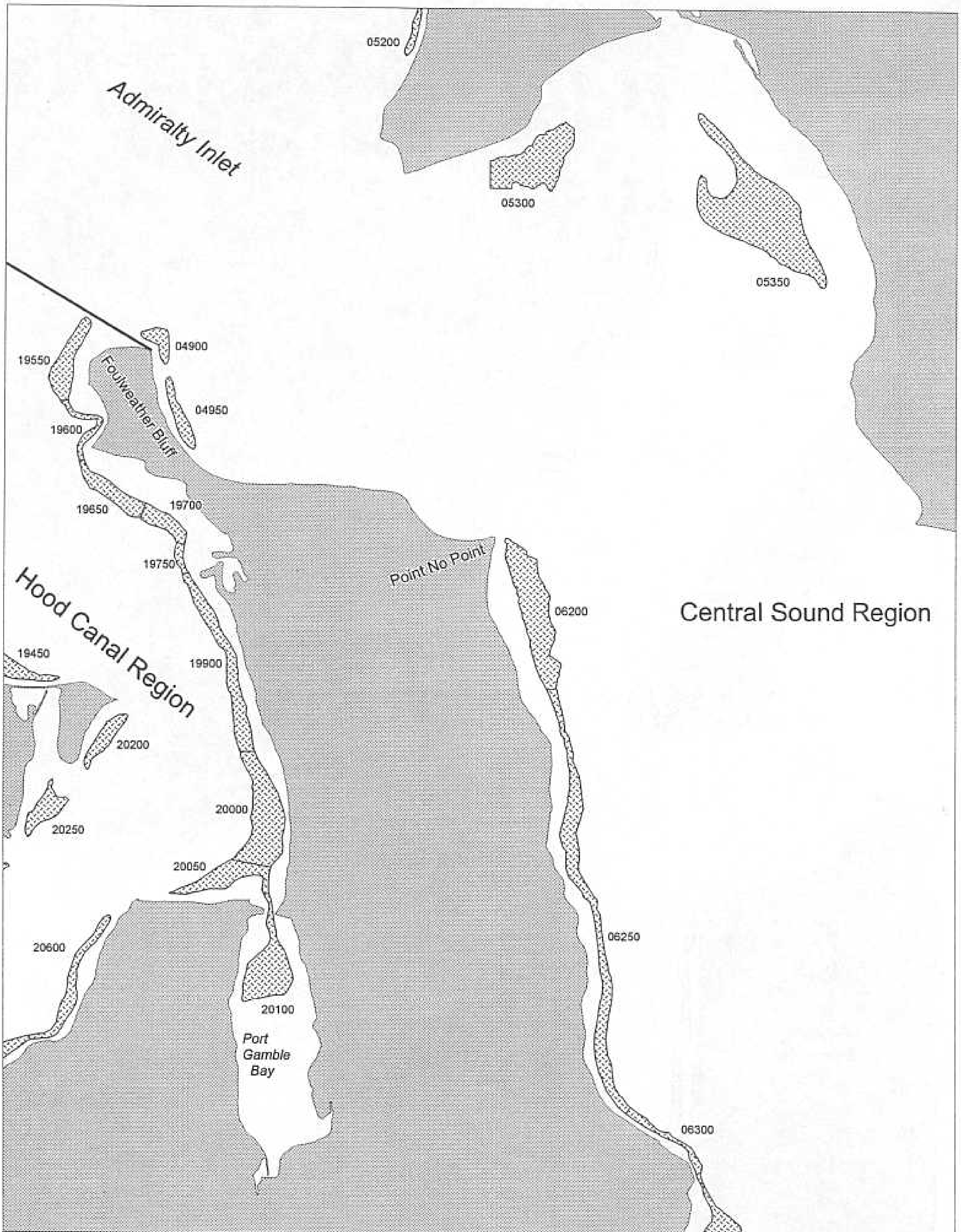

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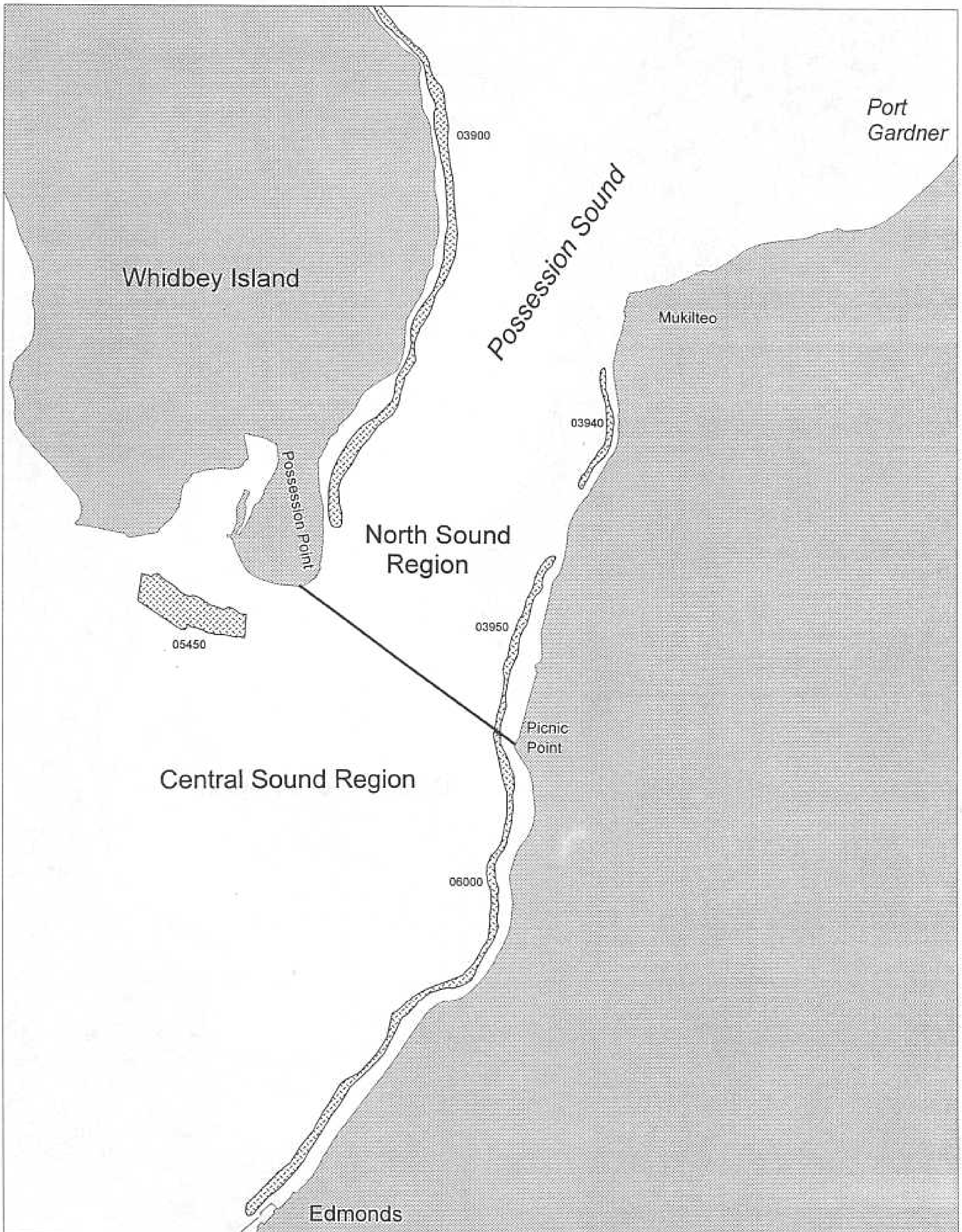

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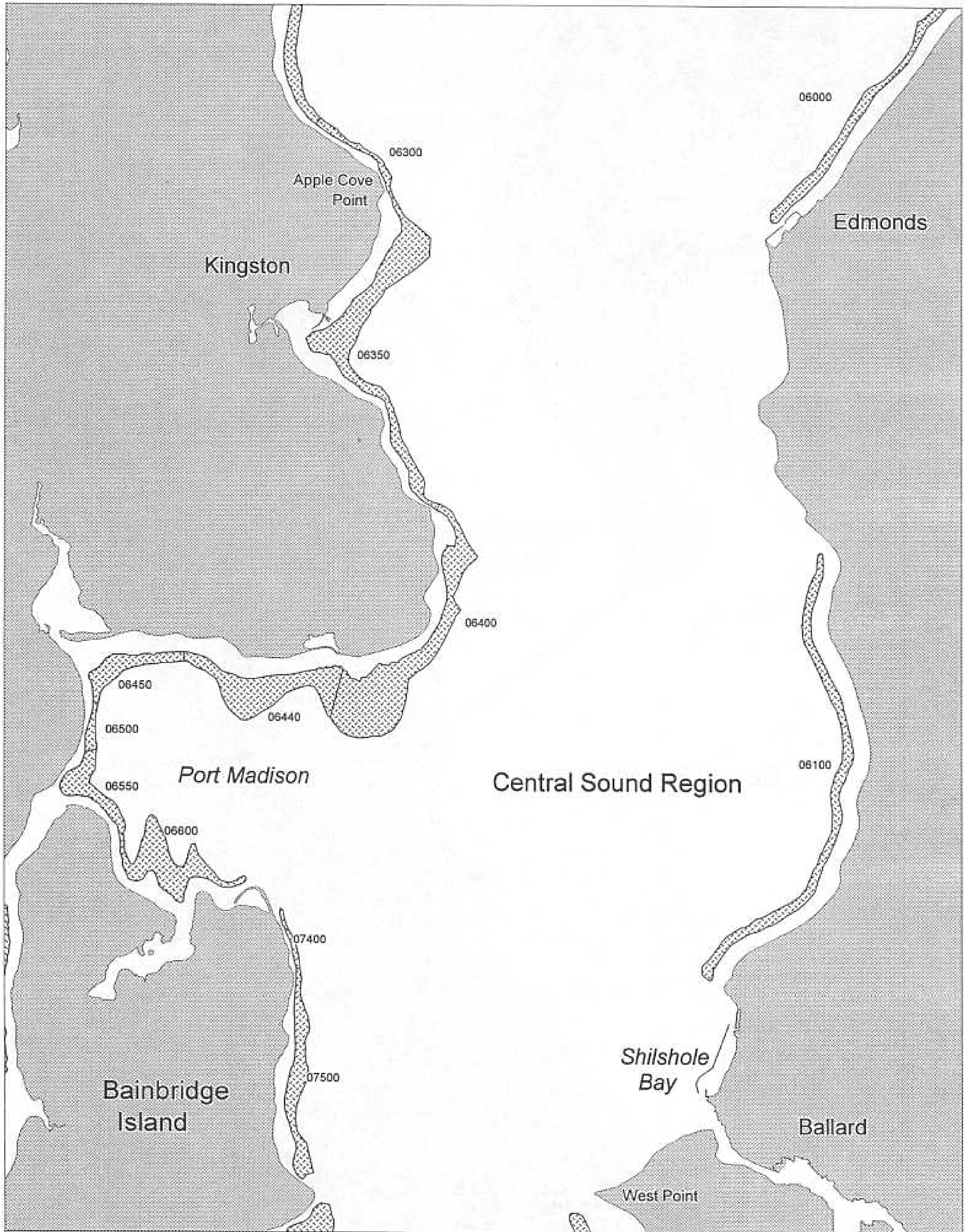

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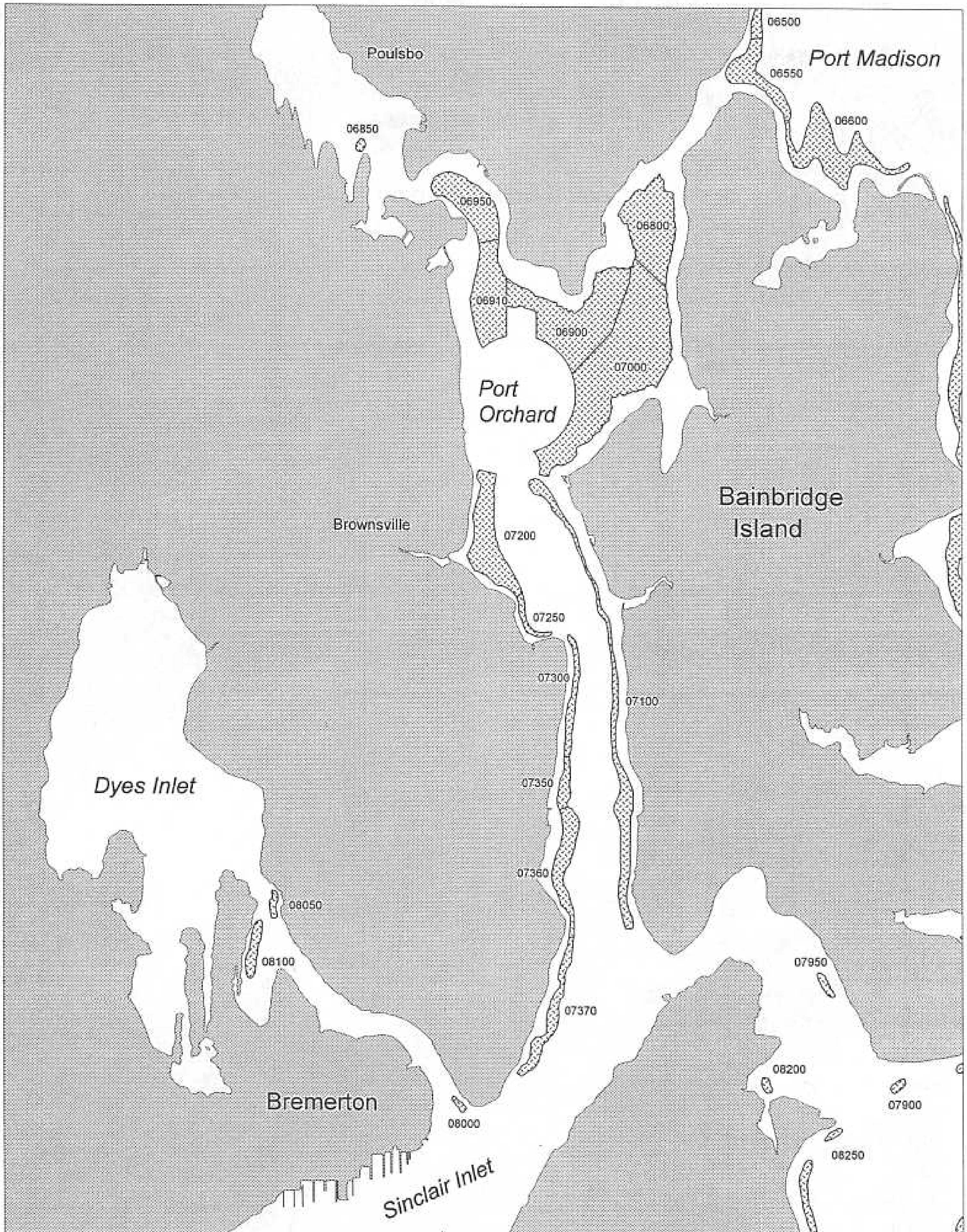

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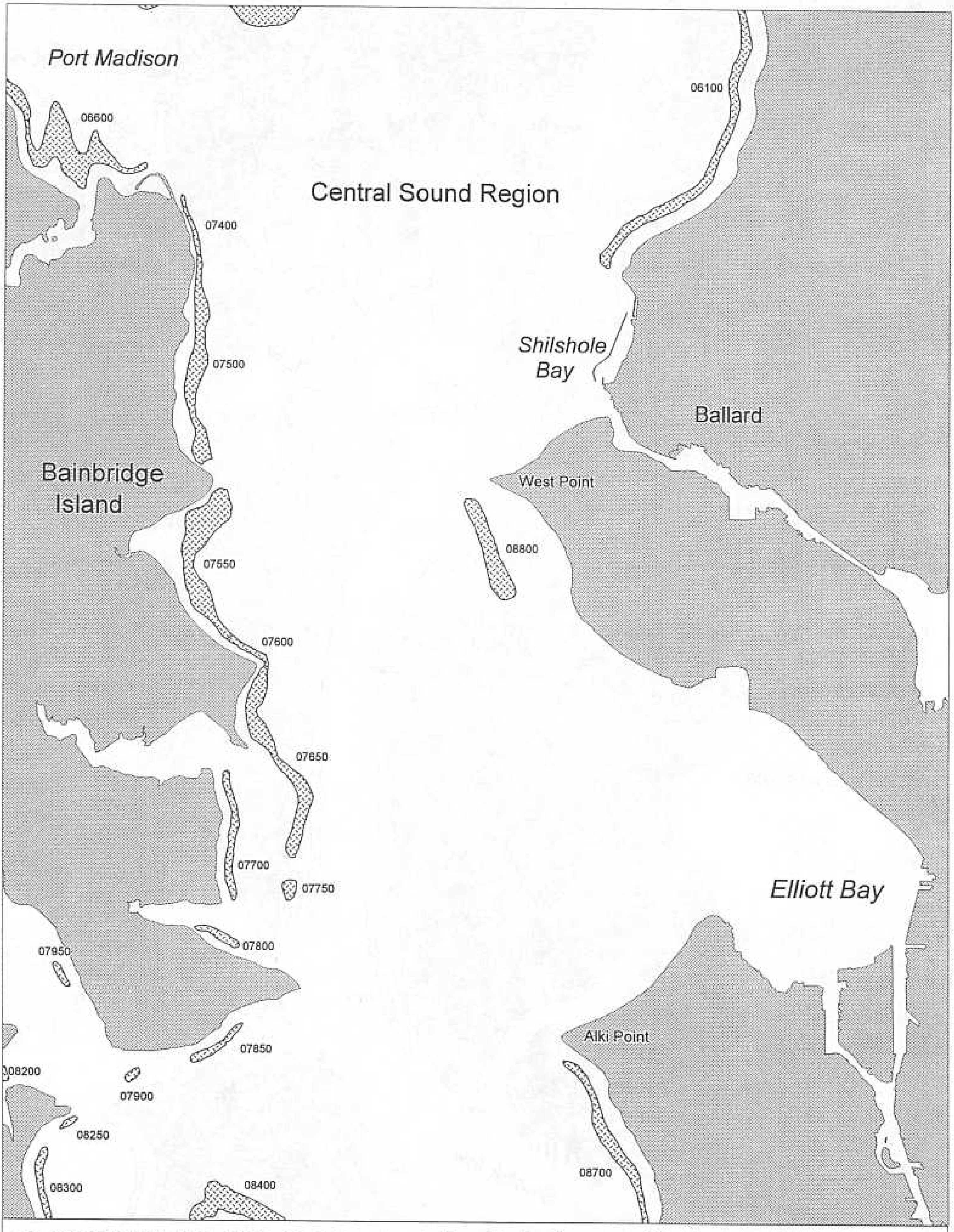

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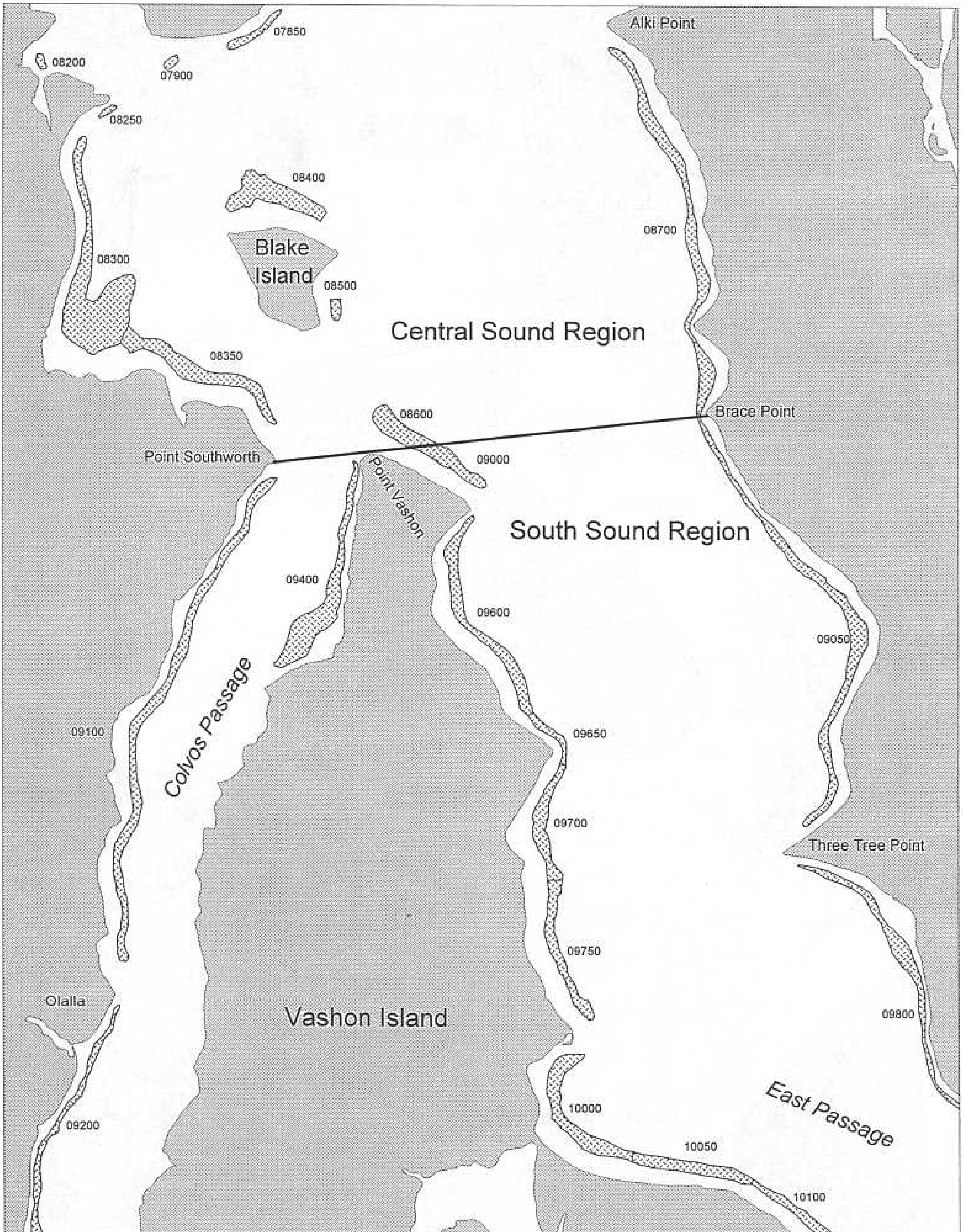

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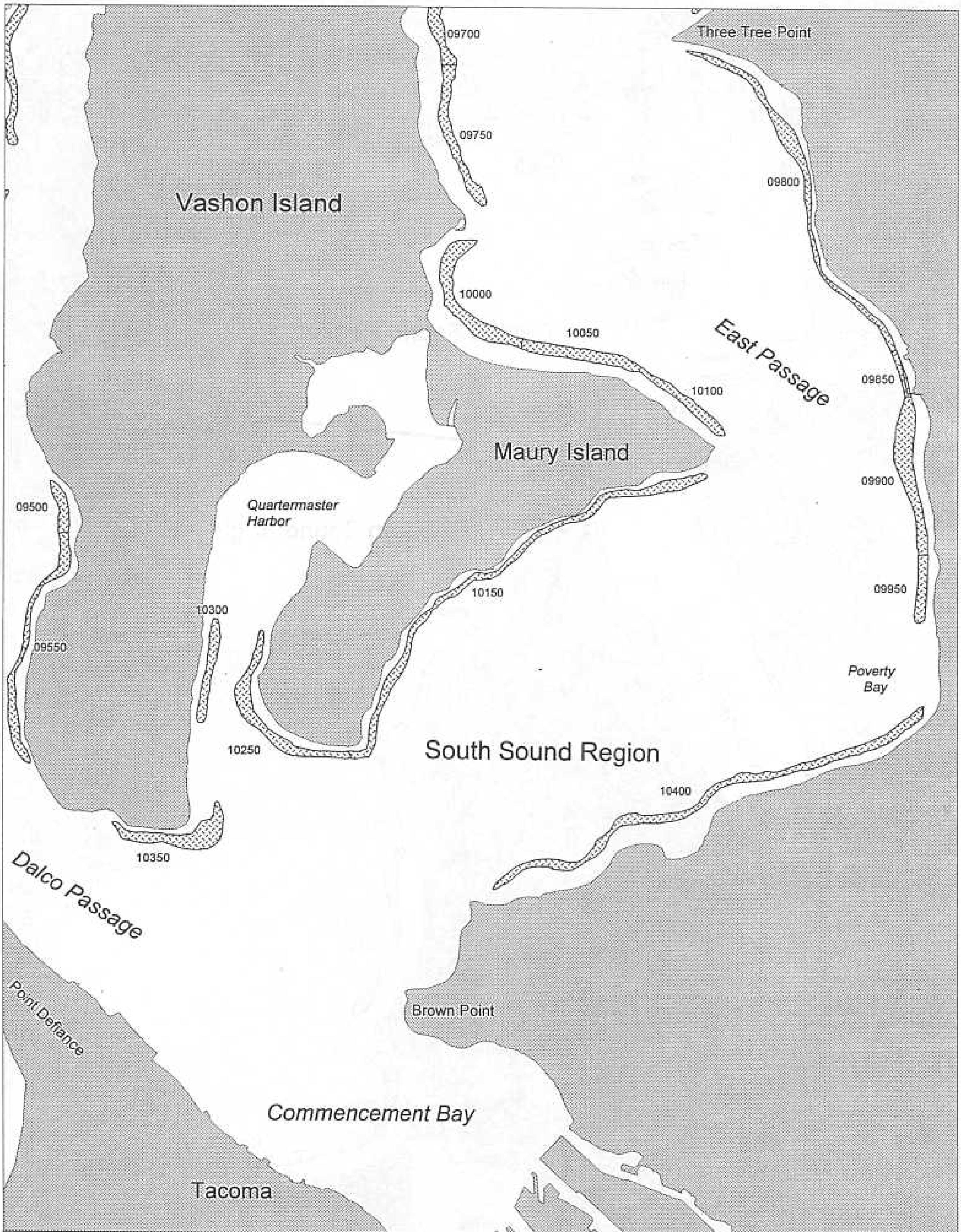

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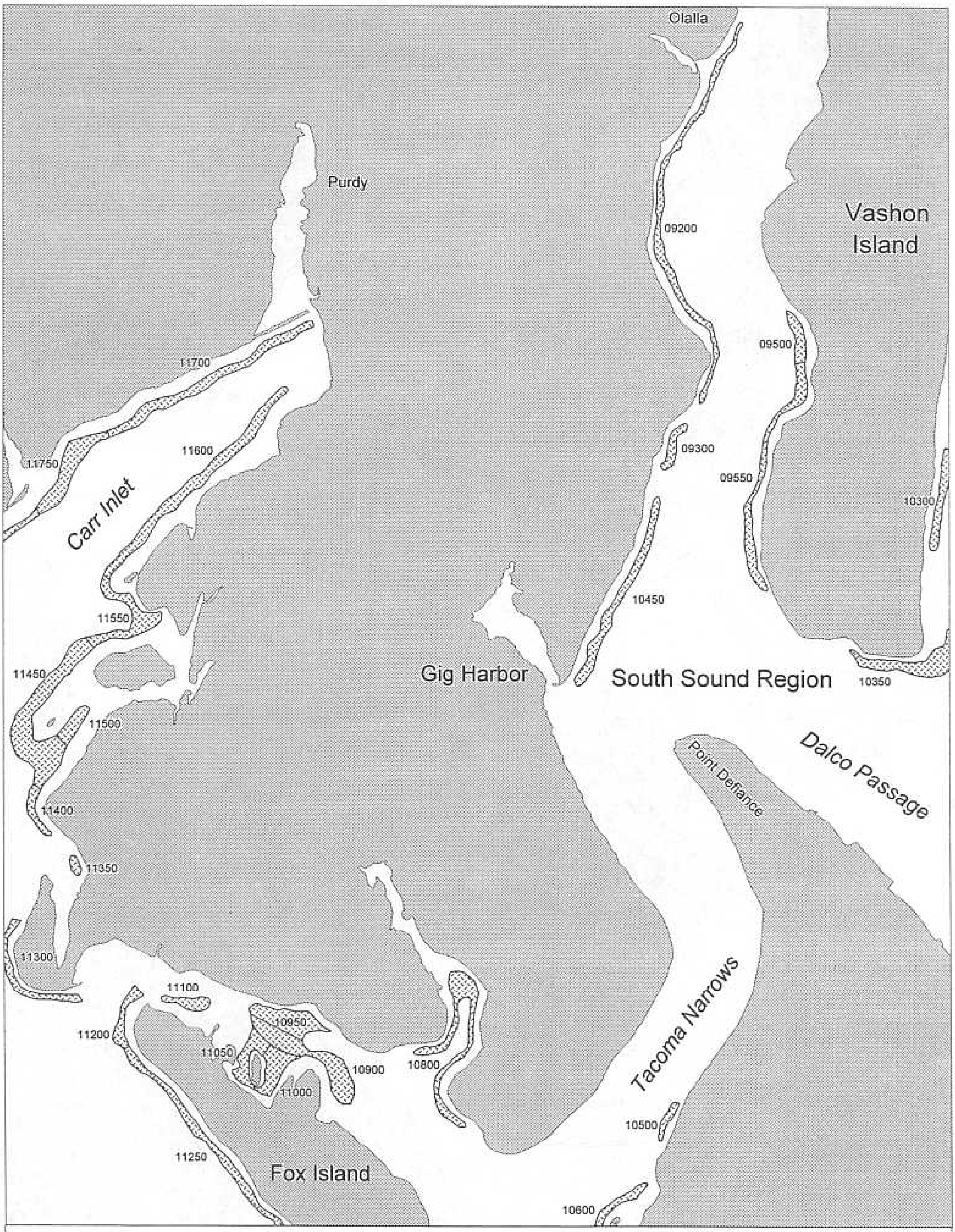

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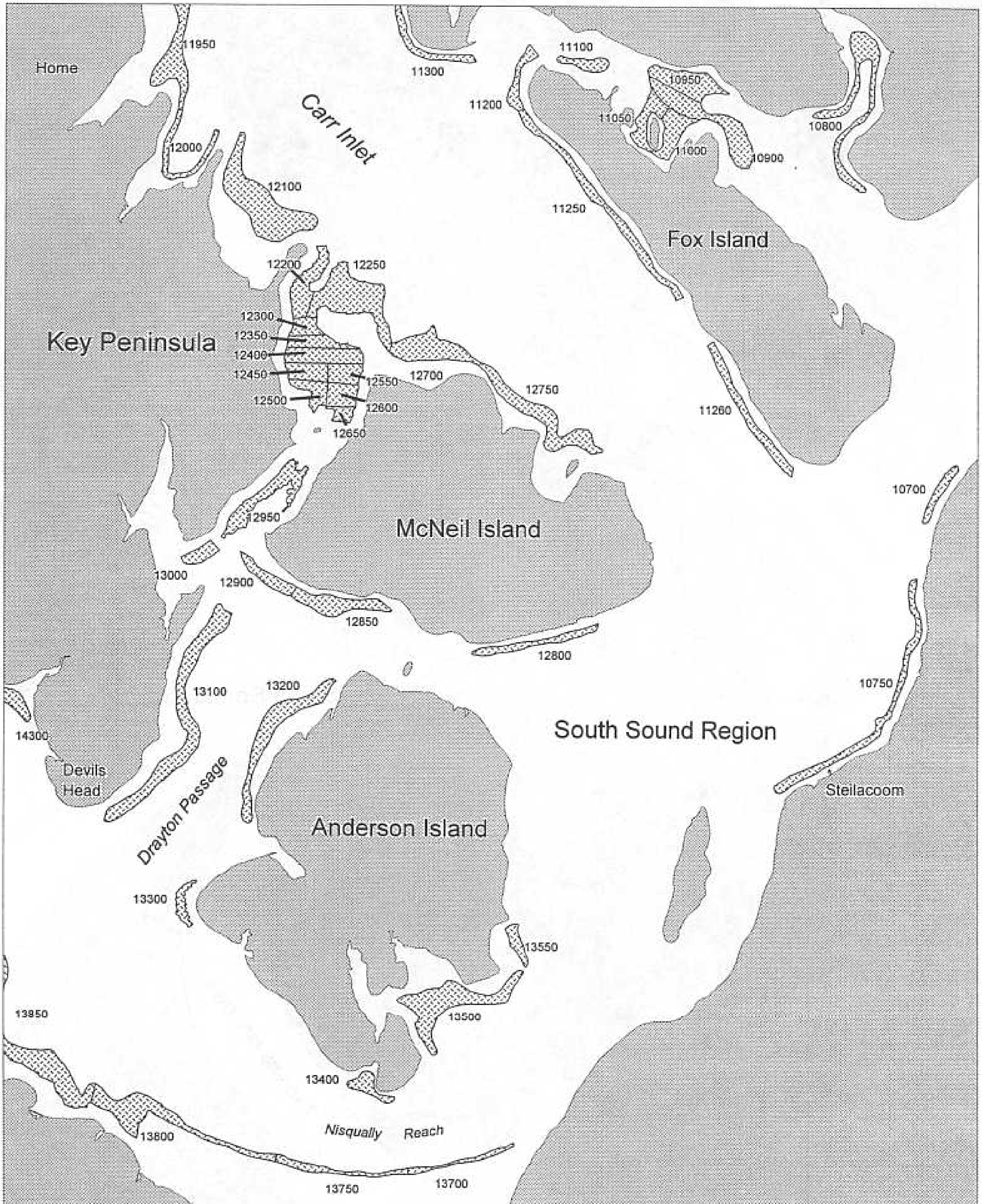

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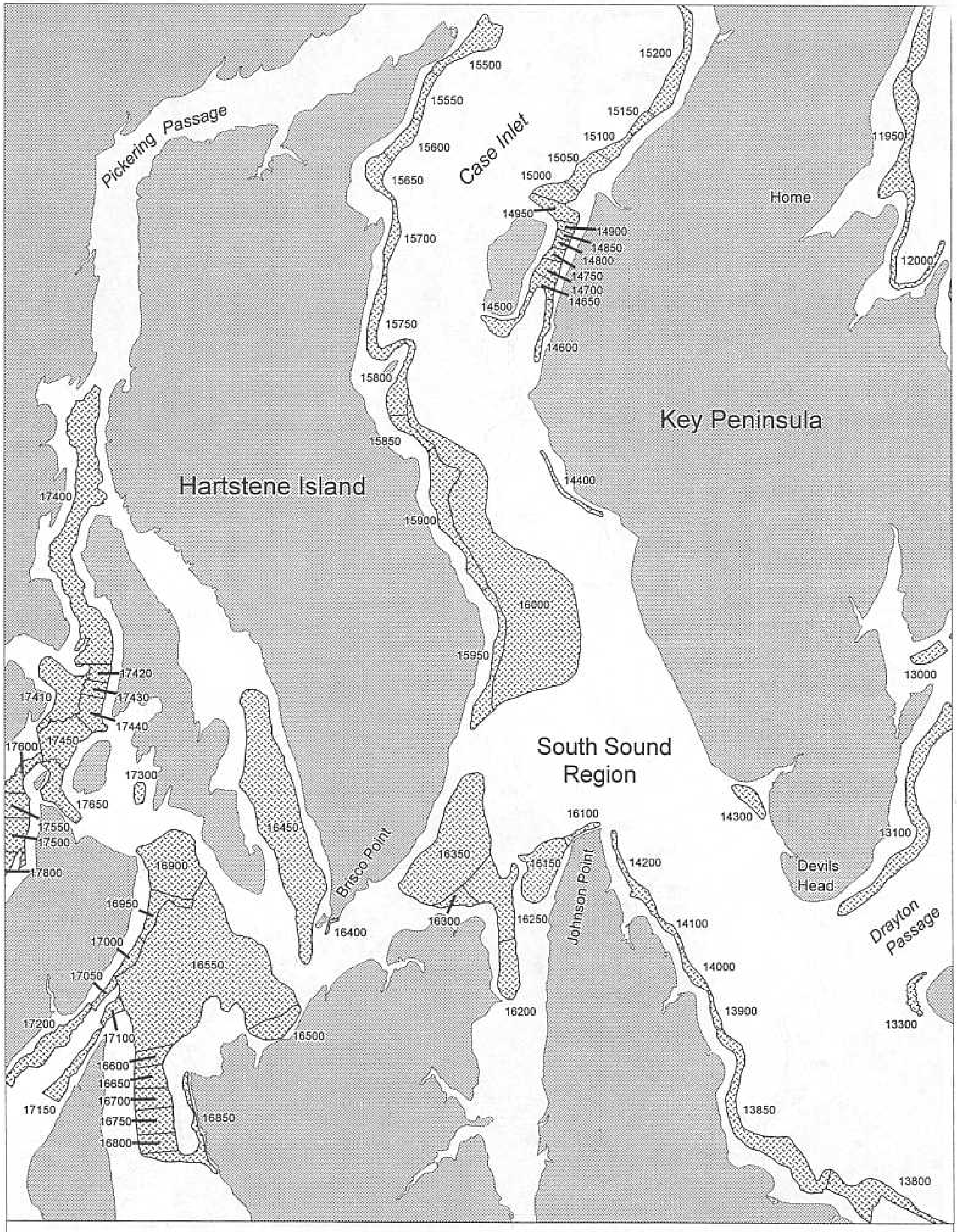

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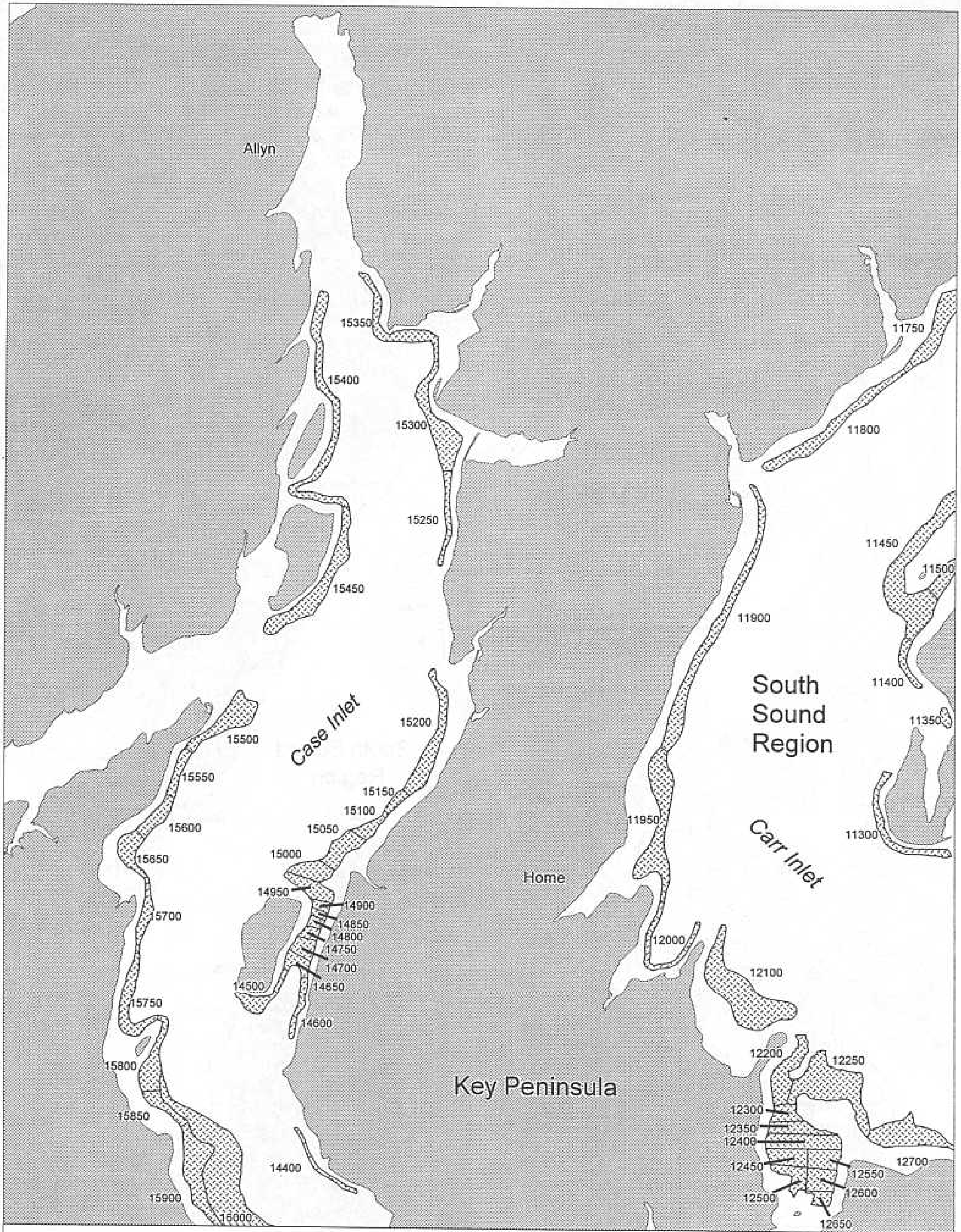

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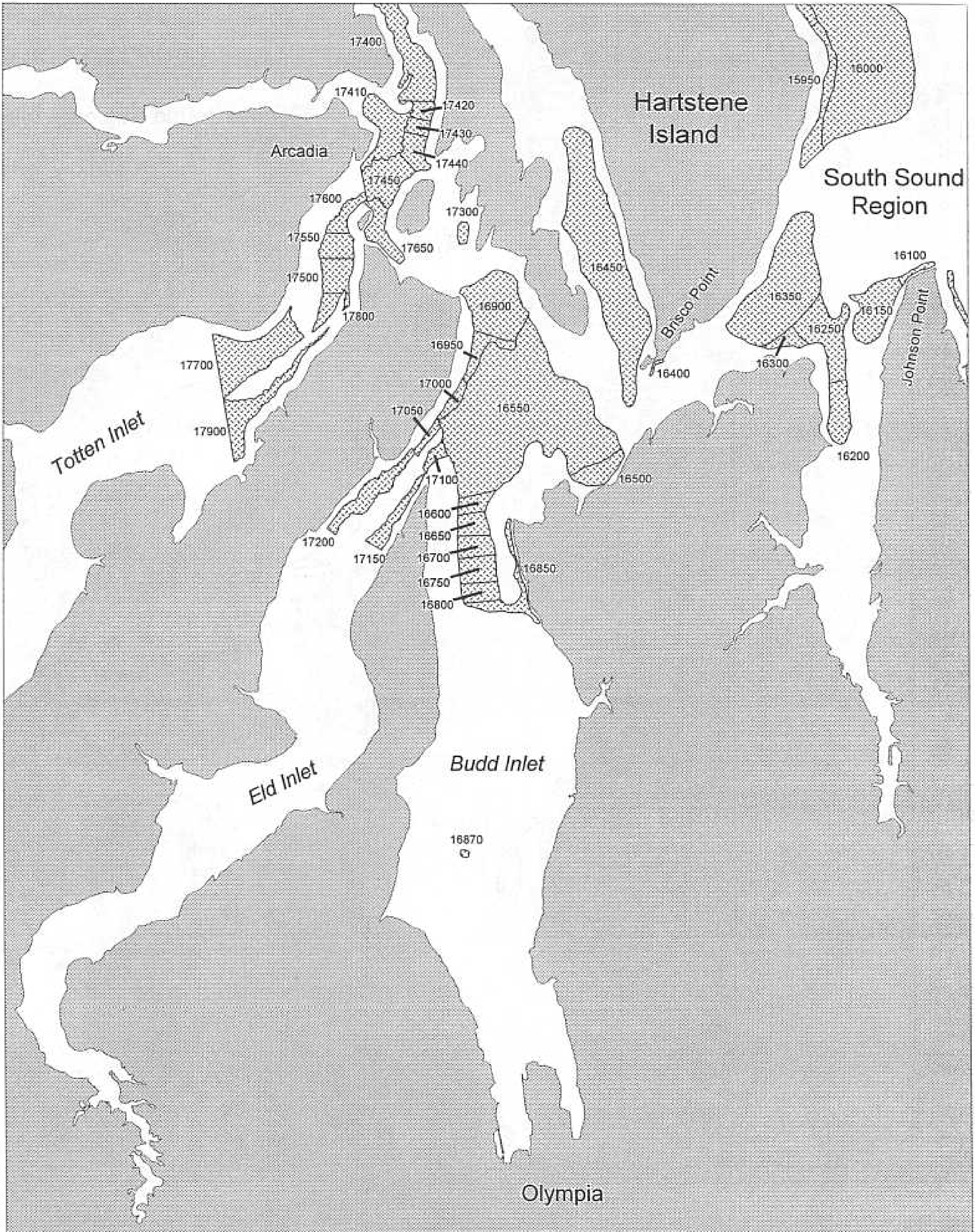

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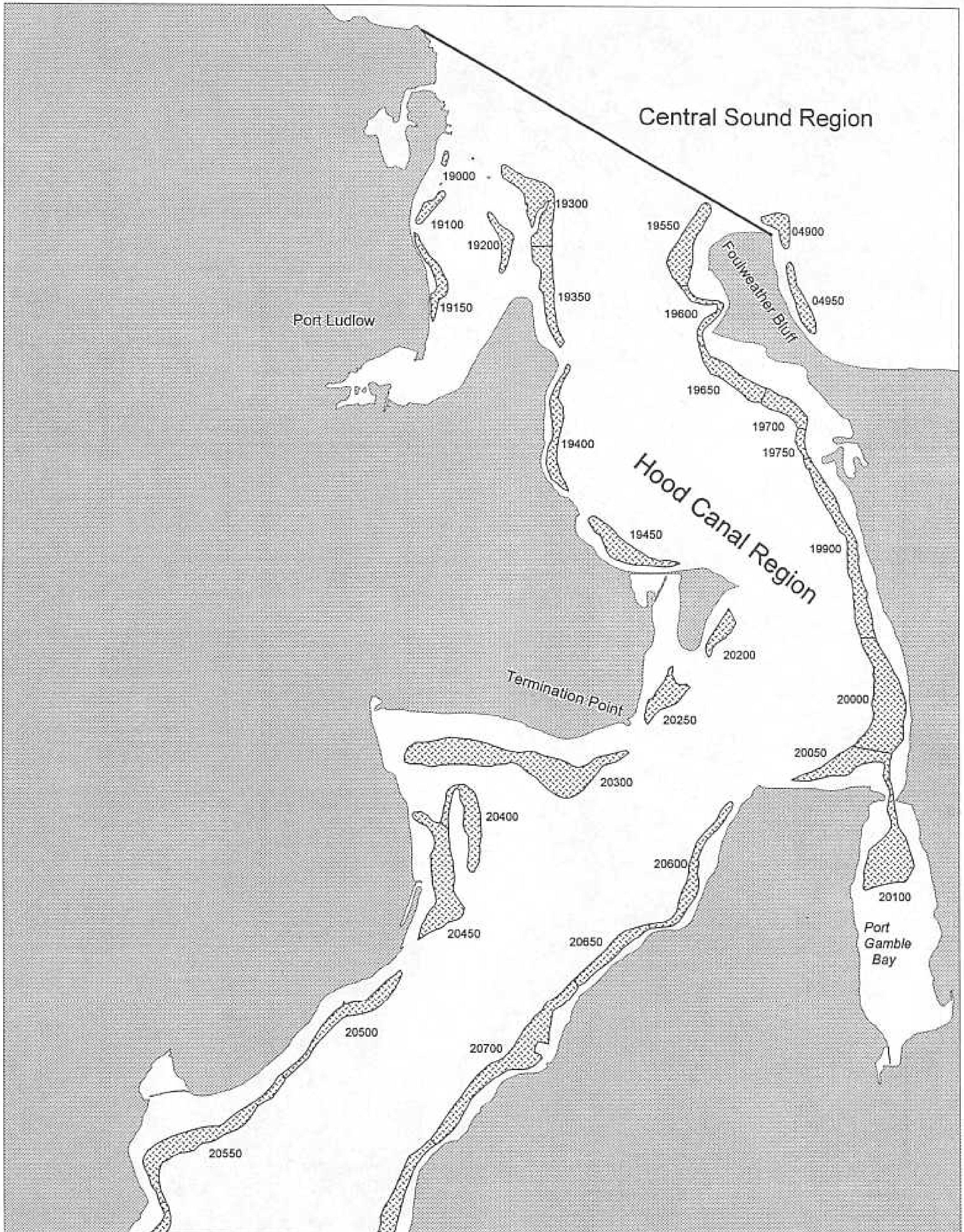

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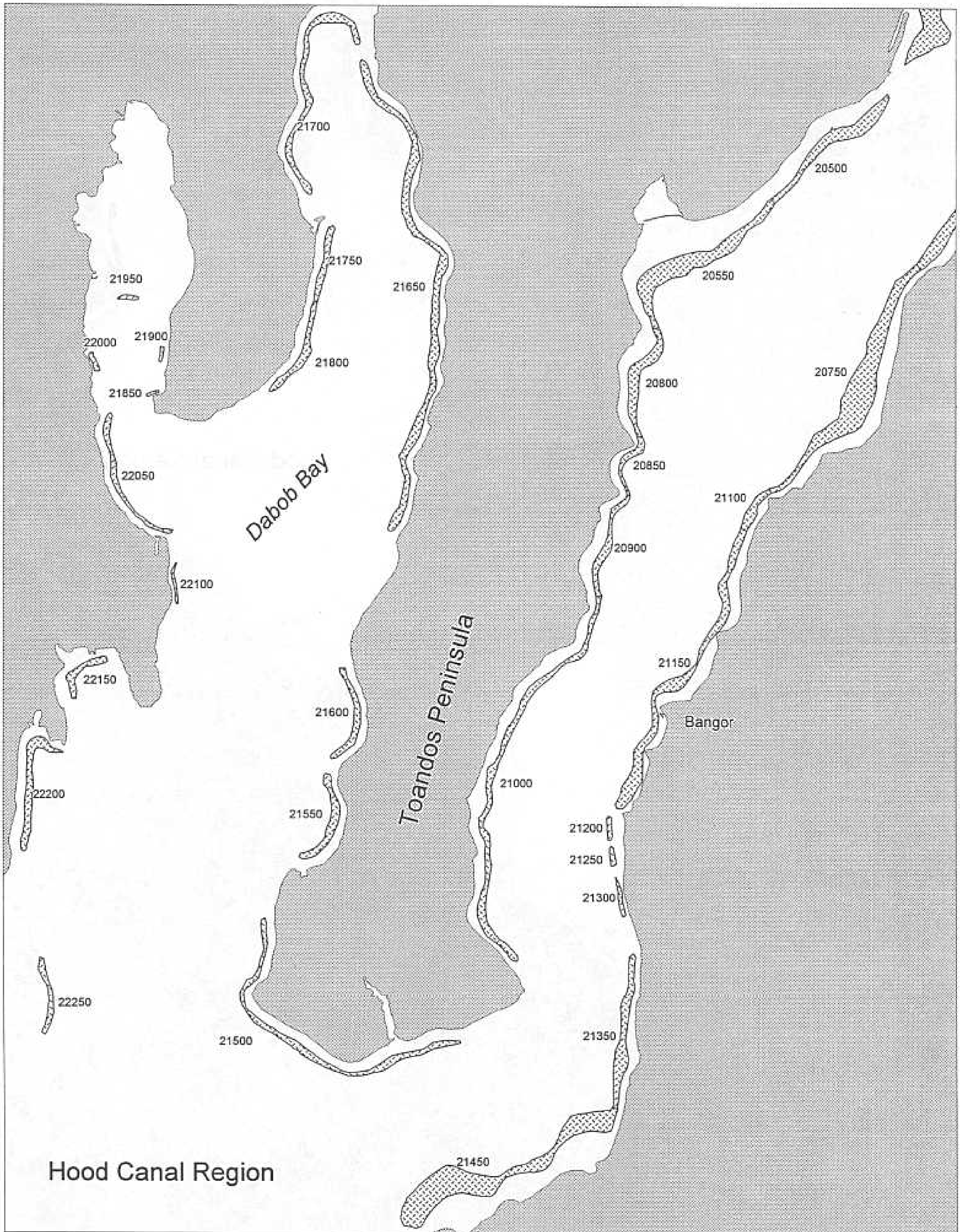

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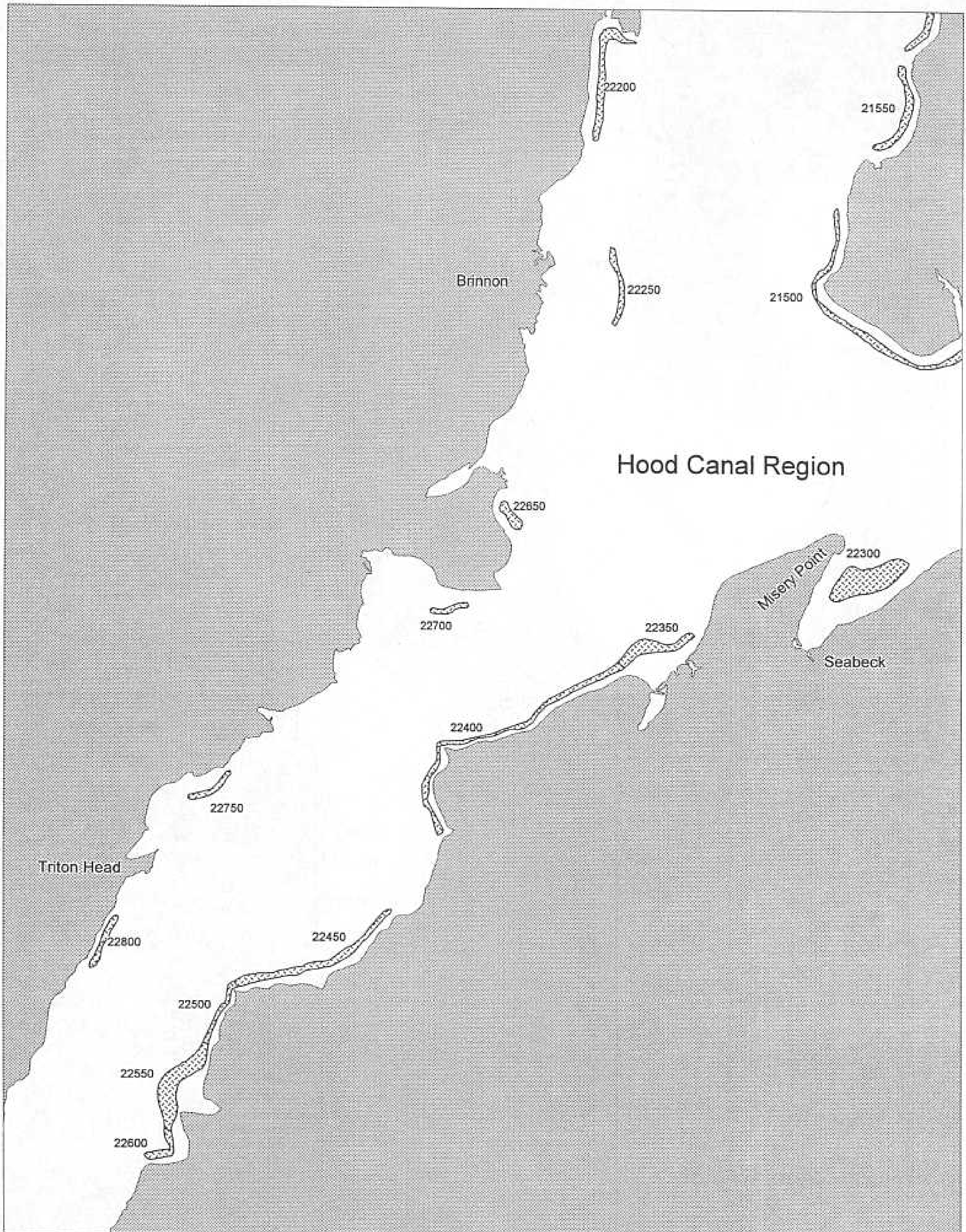

Figure 42. Vicinity Map. To be used as a visual aid only. Tracts may not be to exact proportion or scale.

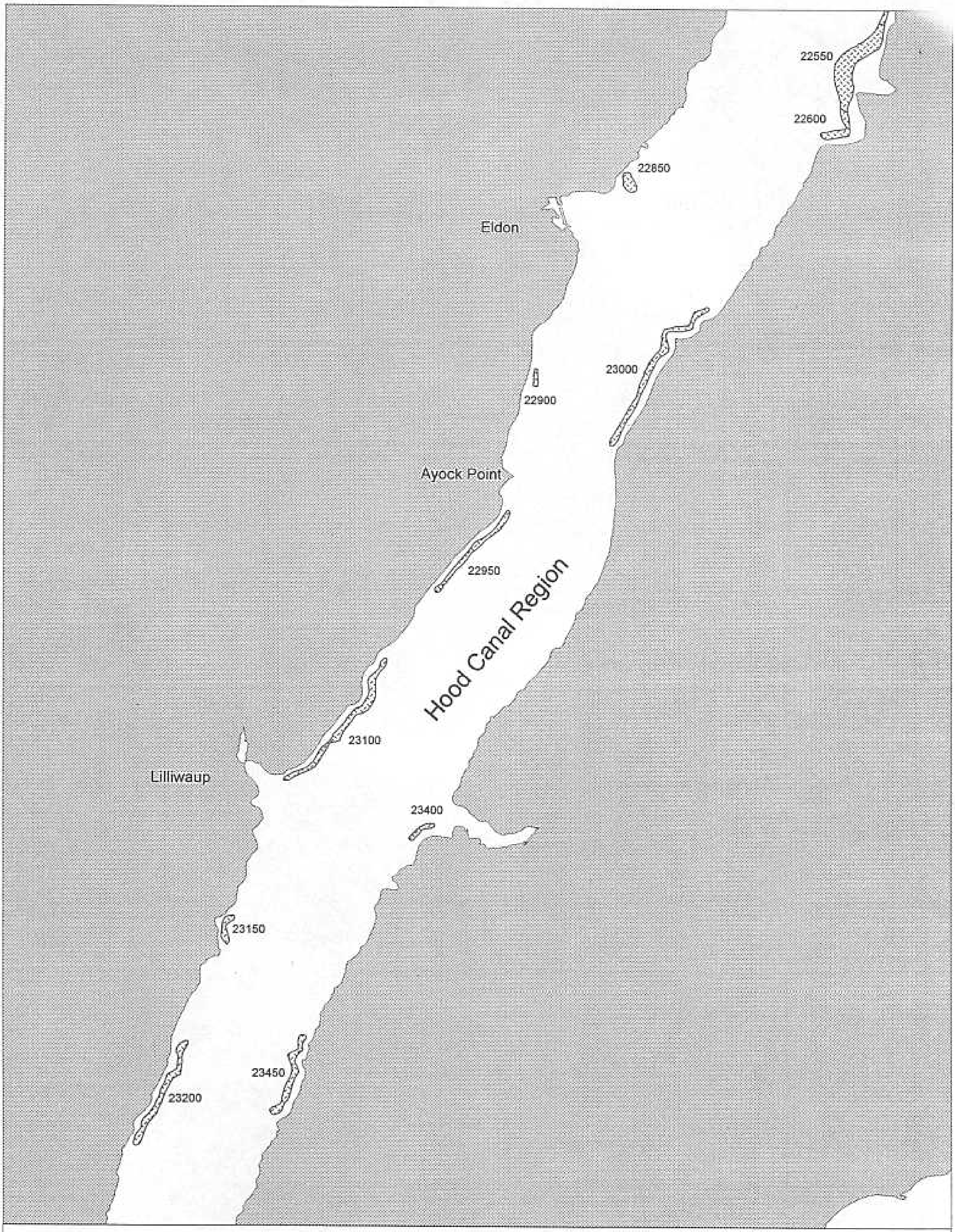

Figure 43. Vicinity Map. To be used as a visual aid only. Tracts may not be to exact proportion or scale.

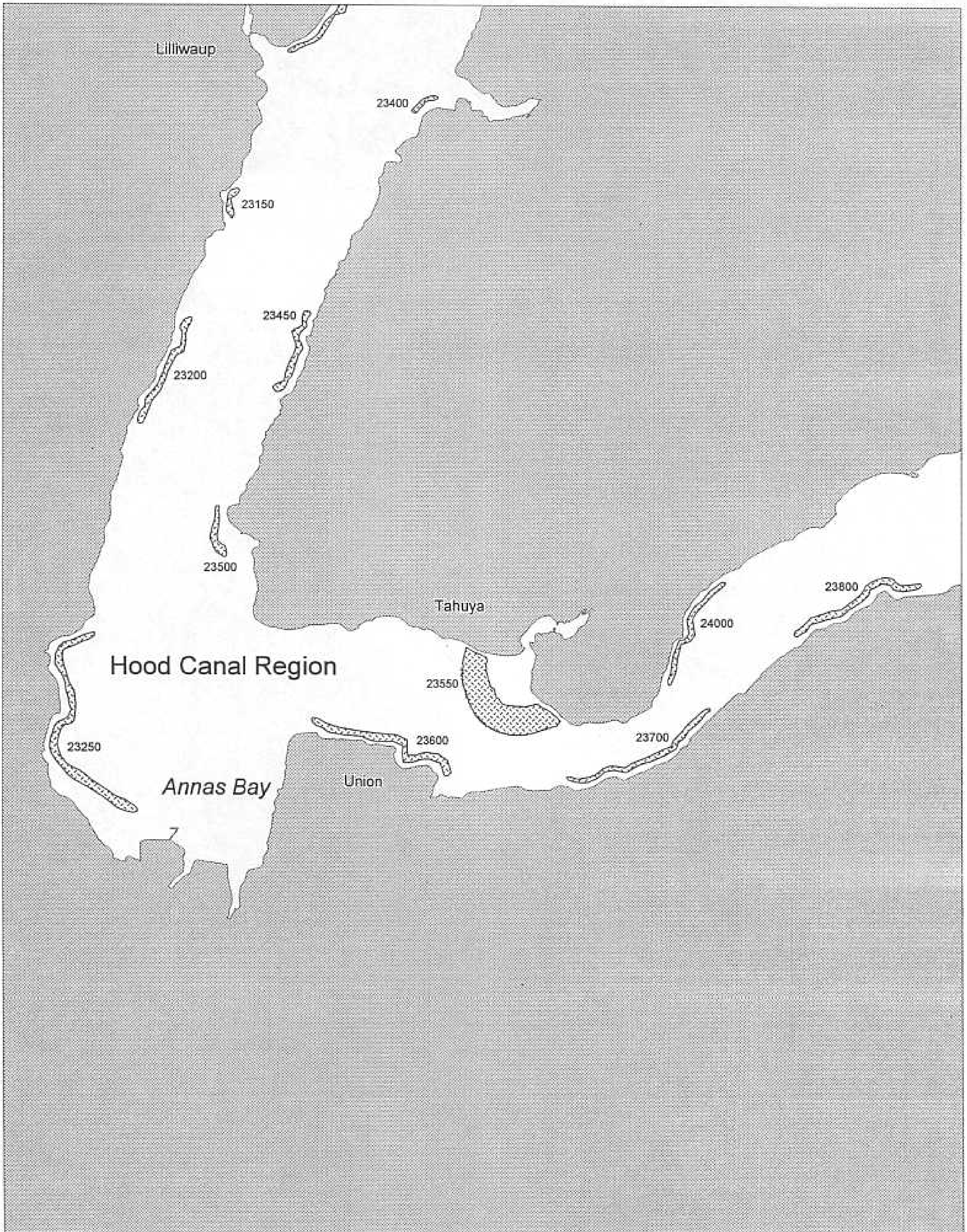

Figure 44. Vicinity Map. To be used as a visual aid only. Tracts may not be to exact proportion or scale.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per sq/ft	Average Geoduck Weight (lb)	Bed Status (see footnote)	Comments
00020	Baadah Point	--	Clallam	--	--	--	--	6	Surveyed in 1997 by WDFW; 11 transects. Substrate shallower than -30 ft. (MLLW) unsuitable for geoduck harvest due to hardpan (clay and gravel). Non-commercial due to very low average density.
00030	Rasmussen Creek	--	Clallam	--	--	--	--	6	Surveyed in 1997 by WDFW; 8 transects. Substrate at western portion of surveyed area is unsuitable for geoduck harvest due to hardpan (clay and gravel). Non-commercial due to very low average density.
00040	East Shipwreck Point	--	Clallam	--	--	--	--	7	Surveyed in 1997 by WDFW; 9 transects. Substrate shallower than -34 ft. (MLLW) unsuitable for geoducks due to rocks and boulders. Deepest occurrence of eelgrass observed is -29 ft. (MLLW). Some areas may be suitable for commercial harvest. Additional transects and acreage estimate is needed to estimate biomass. Pre-fishing survey, including eelgrass survey, is needed to qualify area for harvest.
00050	Sekiu River	--	Clallam	--	--	--	--	6	Surveyed in 1997 by WDFW; 4 transects. Non-commercial due to low average density.
00060	Sekiu Point West	--	Clallam	--	--	--	--	7	Surveyed in 1997 by WDFW; 29 transects. Substrate shallower than -34 ft. (MLLW) unsuitable for geoducks due to rocks and boulders. Deepest occurrence of eelgrass observed is -39 ft. (MLLW). Some areas may be suitable for commercial harvest. Additional transects and acreage estimate is needed to estimate biomass. Pre-fishing survey including eelgrass survey is needed to qualify area for harvest.
00070	Pillar Point	--	Clallam	--	--	--	--	7	Surveyed in 1997 by WDFW; 9 transects. Deepest occurrence of eelgrass observed is -25 ft. (MLLW). Some areas may be suitable for commercial harvest. Additional transects and acreage estimate is needed to estimate biomass. Pre-fishing survey including eelgrass survey is needed to qualify area for harvest.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOTNOTE)	COMMENTS
				NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
00100	Freshwater Bay	510	Clallam	1,683	2,692	0.08	1.6	2	Surveyed in 1997 by PNPTC; 138 transects. Area open and exposed. The nearshore tract boundary is the -40 ft. (MLLW) contour. Harvest began in 1999; 28,601 lbs. reported through 12/31/99.
00150	(X)	--	Clallam	--	--	--	--	11	
00200	(X)	--	Clallam	--	--	--	--	11	
00250	(X)	--	Clallam	--	--	--	--	6/11	Polluted due to a variety of pollution sources.
00300	Siebert Creek (formerly Green Point)	1,197	Clallam	3,897	5,455	0.07	1.4	2/7/8	Surveyed in 1971 and 1975 by WDFW; 17 transects. Area open and exposed. Area subject to PSP closures. 387 acres surveyed by PNPTC in 1996; 130 transects. The nearshore tract boundary is -35 ft. (MLLW) water depth contour or deeper. 810 acres needs a pre-fishing survey, including an eelgrass survey, to qualify the area for commercial harvest. Tract name changed in 1999 to Siebert Creek at request of the WA Dept. of Health. Harvest began in 1999; 75,551 lbs. reported through 12/31/99.
00350	Dungeness Spit	728	Clallam	3,618	5,427	0.11	1.5	7/8	Surveyed in 1971 and 1975 by WDFW; 14 transects. Area open and exposed. Area subject to PSP closures.
00400	New Dungeness	404	Clallam	890	1,780	0.05	--	7/8	Surveyed in 1971 and 1975 by WDFW; 5 transects. Area open and exposed. Area subject to PSP closures.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
00450	Jamestown 1	331	Clallam	819	1,769	0.06	2.2	4	The Dungeness Bay tract, which was included as part of the Jamestown 1 tract, was surveyed in 1971 by WDFW; 6 transects. Portions of this area, both inside and outside of the productive tract, were surveyed in 1998 by PNPTC; 85 transects. The current area and biomass estimate for this tract is revised and based on a 1999 joint state/tribal survey; 96 transects within 331 acres of productive area. The nearshore tract boundary is the -43 ft. (MLLW) depth contour or deeper. The productive tract is between the -43 ft (MLLW) and -67 ft. (MLLW) depth contours.
00500	Jamestown 2	295	Clallam	308	832	0.02	2.7	5	The pre-fishing estimate is from 1993 WDFW, 1996 WDFW, 1996 PNPTC, & 1997 joint WDFW/PNPTC surveys; 107 transects. Number, biomass, and density estimates are adjusted to account for subsequent fishing. 24 acres were added to southern portion of tract #00500 in 1997 when surveys were completed. Eelgrass surveys in 1992, 1996. The nearshore tract boundary is -25 ft (MLLW) water depth contour or deeper. Non-Indian harvest began in 1996. Harvest from 9/1/95 to 12/31/99; 1,438,819 lbs.
00600	Jamestown 4	299	Clallam	517	1,085	0.04	2.1	2	Part of former Jamestown tract surveyed in 1971 and 1975 by WDFW; 30 transects. Fished 1975-1979; 821,000 lbs reported. 75 acres in southern portion of tract were removed from fishable tract due to low density and difficult digging. 215 acres were added to the northern portion of tract #00600 in 1997 when surveys were completed. Estimates are from 1993 WDFW, 1996 PNPTC, & 1997 joint WDFW/PNPTC surveys; 123 transects. Number, biomass, and density estimates are adjusted to account for subsequent fishing. Eelgrass survey in 1992. Eelgrass in central portion of tract extends to the -28 ft contour. Tribal harvest from 9/1/95 to 12/31/99; 1,194,828 lbs.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
00700	Sequim Bay	54	Clallam	213	831	0.09	3.9	8/12	Surveyed in 1976 by WDFW; 13 transects. Area was upgraded by DOH in Jan. 2000. Seeded with hatchery geoduck seed 1987. No harvest January-March due to spawning herring.
00800	Klapot	33	Clallam	10	29	0.01	2.0	6	Surveyed in 1971 by WDFW; 3 transects. Majority closer than 200 yds. from shore. No harvest January-February due to spawning herring. PNPTC survey in 1998, average geoduck density is low.
00900	Travis Spit	91	Clallam	61	122	0.02	--	7	Surveyed in 1971 and 1976 by WDFW; 20 transects. Average geoduck density is low.
01000	Protection Island	256	Jefferson	1,139	**3,074**	**0.10**	**2.7**	2	Surveyed in 1971 and 1978 by WDFW; 21 transects. The current area and biomass estimate for this tract is revised and based on a 1999 joint WDFW/PNPTC survey; 66 transects. The deepest occurrence of eelgrass during the 1999 survey was -29 ft. (MLLW). The nearshore tract boundary is the -31 ft. (MLLW) depth contour or deeper. No harvest should occur within 200 yards of the Protection Island Wildlife Sanctuary. Harvest began in 1999; 40,353 lbs reported.
01050	Dallas Bank	249	Jefferson	759	1,443	0.07	1.9	7/8	Surveyed in 1971 and 1978 by WDFW; 18 transects. Tract is located in close proximity to Protection Island Wildlife Sanctuary and seal haul-out area.
01100	Diamond Point	37	Clallam	81	192	0.05	2.4	6/7/10	Surveyed in 1970 by WDFW; 7 transects. No dig samples, avg. weight inferred from other Discovery Bay samples. Majority of tract is closer than 200 yards from shore. 1996 PNPTC reconnaissance survey indicates average geoduck density is low.
01150	Eagle Creek	48	Clallam Jefferson	77	192	0.04	2.5	6/7	Surveyed in 1970 and 1982 by WDFW; 28 transects. 1996 PNPTC reconnaissance survey indicates average geoduck density is low.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
01200	Gardiner	83	Jefferson	300	720	0.08	2.4	6/7/10/12	Surveyed in 1970 by WDFW; 12 transects. No dig samples; avg. weight inferred from other Discovery Bay samples. Portion closer than 200 yards from shore. No harvest February-April due to spawning herring.1996 PNPTC reconnaissance survey indicates average geoduck density is low.
01250	Kalset Point	63	Jefferson	290	638	0.11	2.2	6/7/12	Surveyed in 1970 and 1982 by WDFW; 23 transects. No harvest February-April due to spawning herring. 1996 PNPTC reconnaissance survey indicates average geoduck density is low.
01300	Mill Point	246	Jefferson	1,480	3,552	0.14	2.4	6/7/12	Surveyed in 1970 by WDFW; 8 transects. No dig samples; average weight inferred from other Discovery Bay samples. Substrate very muddy. May be polluted. 1996 PNPTC reconnaissance survey indicates average geoduck density is low. Harvest of 292 lbs reported in 1999 and attributed to tract #03100.
01350	Woodmans	11	Jefferson	7	17	0.01	2.4	6/7/10/12	Surveyed in 1970 by WDFW; 2 transects. No dig samples; average weight inferred from other Discovery Bay samples. Portions closer than 200 yards from shore. 1996 PNPTC reconnaissance survey indicates average geoduck density is low.
01400	Adelma Beach	64	Jefferson	29	69	0.01	2.4	6/10/12	Surveyed in 1970 by WDFW; 7 transects. No dig samples; average weight inferred from other Discovery Bay samples. PNPTC surveyed 1996; 21 transects. Joint WDFW/PNPTC survey in 1997; 23 transects. Average geoduck density is low. Majority of tract is closer than 200 yards from shore. No harvest during February-April due to spawning herring.
01450	Tukey	199	Jefferson	153	541	0.02	2.4	6/12	Surveyed in 1970 by WDFW; 9 transects. No dig samples; average weight inferred from other Discovery Bay samples. PNPTC surveyed 1996; 28 transects. Joint WDFW/PNPTC survey in 1997; 17 transects. Average geoduck density is low. No harvest during February-April due to spawning herring.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
01500	Beckett Point	55	Jefferson	67	160	0.03	2.4	6/12	Surveyed in 1970 by WDFW; 9 transects. No dig samples, average weight inferred from other Discovery Bay samples. PNPTC surveyed in 1996; 28 transects. Joint WDFW/PNPTC survey in 1997; 23 transects. Average geoduck density is low. No harvest during February-April due to spawning herring.
01550	Beckett Point North	12	Jefferson	56	133	0.11	2.4	6/7/10	Surveyed in 1970 by WDFW; 3 transects. No dg samples; average weight inferred from other Discovery Bay samples. 1996 PNPTC reconnaissance survey indicates low density. Majority of tract is closer than 200 yards from shore.
01600	Cape George	12	Jefferson	92	221	0.18	2.4	6/7	Surveyed in 1970 by WDFW; 5 transects. No dig samples; average weight inferred from other Discovery Bay samples. 1996 PNPTC reconnaissance survey indicates average geoduck density is low. A small area of the tract may lie within a marina closure zone.
01650	Cape George North	209	Jefferson	278	556	0.03	--	6	Surveyed 1970 and 1976 by WDFW; 10 transects. Average geoduck density is low.
01700	Middle Point	86	Jefferson	105	231	0.03	2.2	5/6/7	Surveyed in 1985 by WDFW. Fished 1986-87; 360,851 lbs reported. Post harvest survey 1988 by WDFW; 26 transects. Figures in table are from 1988 survey. Possible pollution due to Port Townsend sewage effluent.
02000	(X)	--	San Juan	--	--	--	--	11	Harvest of 238 lbs. reported in 1999 and attributed to tract #20000.
02100	(X)	--	San Juan	--	--	--	--	11	
02200	(X)	--	San Juan	--	--	--	--	11	
02300	(X)	--	San Juan	--	--	--	--	11	
02400	(X)	--	San Juan	--	--	--	--	11	

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
02500	(X)	--	San Juan	--	--	--	--	6/11	Portion of tract may be within a closure zone established for the sewer outfall for the Fisherman Bay Sewer District.
02600	(X)	--	San Juan	--	--	--	--	11	
02700	(X)	--	San Juan	--	--	--	--	11	
02800	(X)	--	San Juan/ Whatcom	--	--	--	--	11	
02900	(X)	--	Whatcom	--	--	--	--	11	
02950	(X)	--	Whatcom	--	--	--	--	11	
02990	(X)	--	Whatcom	--	--	--	--	11	
03000	(X)	--	Island	--	--	--	--	11	
03050	(X)	--	Island	--	--	--	--	11	
03100	Pt. Partridge	586	Island	1,247	2,120	0.05	1.7	2/10	Surveyed in 1971 and 1974 by WDFW; 31 transects. 84 acres in north end fished 1977-79; 27,000 lbs reported. State Parks has withdrawn about 20 acres at the north end. Surveyed in 1997 and 1998 by WDFW; 141 transects. Pre-fishing biomass and tract acreage is based on 1997 and 1998 surveys. Eelgrass extends to a maximum depth of -28 ft. (MLLW) in surveyed portion. Nearshore tract boundary is the -30 ft. (MLLW) contour or deeper. Southern portion of bed needs a pre-fishing survey. The current harvest began in 1999; 7,928 lbs. reported.
03150	(X)	--	Island	--	--	--	--	11	
03200	(X)	--	Island	--	--	--	--	11	
03250	(X)	--	Island	--	--	--	--	11	

All reported catches before August 1, 1991 have been reduced 10% for water loss.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per Sq/Ft	Average Geoduck Weight (LB)	Bed Status (See Footnote)	Comments
03300	(X)	--	Island	--	--	--	--	11	
03350	(X)	--	Island	--	--	--	--	11	
03400	Dines Point	172	Island	80	160	0.01	--	6/7/10/12	Surveyed in 1971 by WDFW; 5 transects. Portion closer than 200 yards from shore. No harvest during February-April due to spawning herring. Average geoduck density is low.
03450	Holmes Harbor	55	Island	33	66	0.01	--	6/7/10/12	Surveyed in 1971 by WDFW; 2 transects. Portion closer than 200 yards from shore. No harvest during February-April due to spawning herring. Average geoduck density is low.
03500	Rocky Point	92	Island	92	184	0.02	--	6/7/10	Surveyed in 1971 by WDFW; 3 transects. Portion closer than 200 yards from shore. Average geoduck density is low.
03550	Langley	56	Island	95	190	0.04	--	6	Surveyed in 1971 by WDFW; 2 transects. Polluted, Langley sewage treatment plant.
03600	(X)	--	Island	--	--	--	--	11	
03650	(X)	--	Island	--	--	--	--	11	
03700	(X)	--	Island	--	--	--	--	11	
03750	(X)	--	Island	--	--	--	--	11/12	No harvest during February-April due to spawning herring.
03800	(X)	--	Island	--	--	--	--	11	Harvest of 3,254 lbs. reported in 1999. Erroneous tract number reported on fish receiving ticket will be researched and landings will be assigned to the appropriate tract in the 2001 Geoduck Atlas.
03900	Randall Point	357	Island	897	1,794	0.06	--	6/7/10	Surveyed in 1971 and 1977 by WDFW; 19 transects. Portion closer than 200 yd from shore. Portion near Clinton may be polluted by failing onsite systems.
03910	Gedney Island North	82	Snohomish	95	190	0.03	--	6/7/10	Surveyed in 1971 by WDFW; 3 transects. Surveyed by Tulalip Tribes in 1999; 58 lbs harvested for dig samples. Portion closer than 200 yards from shore. Average geoduck density is low.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
03920	(X)	--	Snohomish	--	--	--	--	11	
03930	Gedney Island South	23	Snohomish	63	126	0.06	--	8	Surveyed in 1971 by WDFW; 2 transects.
03940	Elliot Point	69	Snohomish	12	24	0.00	--	6/7/10	Surveyed in 1971 by WDFW; 4 transects. Portions of the tract are closer than 200 yards from shore. The portion of the tract near Clinton may be polluted by failing onsite systems. Average geoduck density is low.
03950	Picnic Point North	103	Snohomish	217	324	0.05	1.5	6/7/10	Surveyed in 1970, 1971, 1975, and 1980 by WDFW; 38 transects total for tract #'s 03950 & 06000. Number and biomass adjusted to account for Central/North Sound regional boundary line. A portion of this tract may be polluted due to Olympus Terrace sewage treatment outfall.
04000	Hudson Point	128	Jefferson	243	388	0.04	1.6	1/6/7/8	Surveyed in 1985 by WDFW. Fished 1986-87. 354,648 lbs reported. Post harvest survey in 1988 by WDFW; 35 transects. Possible pollution due to marina and urban runoff.
04050	(X)	--	Jefferson	--	--	--	--	11	
04100	Port Townsend	700	Jefferson	1,412	2,824	0.05	--	6/7	Surveyed in 1968 and 1978 by WDFW; 12 transects. Substrate very muddy; excessive water depth. Possible pollution due to marina and urban runoff.
04200	(X)	--	Jefferson	--	--	--	--	11	
04250	Kala Point/Old Fort Townsend Recovery Bed	65	Jefferson	14	26	0.01	1.8	9/12	Surveyed in 1985 by WDFW. Fished 1985-86; 441,894 lbs reported. Post harvest survey in 1987 by WDFW; 20 transects. Seeded with hatchery geoduck seed 1988. Surveyed in May 1993 by WDFW; 20 transects. Population recovering slowly. No harvest during February-March due to spawning herring. Average pre-fishing density .10 geo/sq ft.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
04300	Crane Point	36	Jefferson	54	146	0.03	2.7	6/12	Surveyed in 1985 by WDFW. Fished 1986-87; 207,261 lbs reported. Post harvest survey in 1988 by WDFW; 16 transects. Polluted due to Navy sewage effluent. No harvest during February-March due to spawning herring. Average geoduck density is low.
04350	Walan 1 & 2 Recovery Bed	152	Jefferson	112	269	0.02	2.4	5/9/12	Surveyed in 1975 and 1976 by WDFW. Fished 1977-80 under old tract name of Kilisut Spit (64 acres) 1,660,000 lbs reported. Surveyed in 1985 by WDFW. Fished again 1986-87 under Walan 1 & 2; 770,870 lbs reported. Post harvest survey in 1988 by WDFW; 24 transects. Surveyed in September 1993 by WDFW; 24 transects. Population recovering slowly. No harvest during February-March due to spawning herring. Average pre-fishing density .07 geo/sq ft.
04400	Kilisut 2	23	Jefferson	126	284	0.13	2.3	8/12	Surveyed in 1985 by WDFW; 14 transects. DNR decided not to sell geoducks. This tract is partially within a joint agreement area for Fort Flagler State Park, but none of the bed will be withdrawn by State Parks. No harvest during February-March due to spawning herring.
04450	Kilisut 1	32	Jefferson	142	285	0.10	2.0	1/8	Surveyed in 1985 by WDFW. Fished 1986-87; 326,016 lbs reported. Post harvest survey in 1988 by WDFW; 13 transects. This tract is partially within the joint agreement area for Fort Flagler State Park, but none of the bed will be withdrawn by State Parks.
04500	(X)	--	Jefferson	--	--	--	--	6/11/12	No harvest during February-March due to spawning herring. May be polluted from Navy toxic waste.
04550	(X)	--	Jefferson	--	--	--	--	11/12	No harvest during February-March due to spawning herring.
04600	(X)	--	Jefferson	--	--	--	--	11/12	No harvest during February-March due to spawning herring.
04650	(X)	--	Jefferson	--	--	--	--	11	

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
04700	Indian Island South /Kinney Point Recovery Bed	76	Jefferson	298	462	0.09	1.6	9	Surveyed in 1985 by WDFW. Fished 1985-86; 525,113 lbs reported. First post harvest survey 1987. Combined into one tract, second post harvest survey June 1993; 22 transects; population recovered from 0.02 geo/sq ft in 1987 to 0.09 geo/sq ft in 1993. Average pre-fishing density .14 geo/sq ft
04750	Oak Bay 1	17	Jefferson	207	332	0.28	1.6	8/7	Surveyed in 1985 by WDFW. DNR tried to sell geoducks in fall of 1985 and combined Oak Bay 1 with Oak Bay 2 under the name of Oak Bay; didn't sell. Tried to sell geoduck again in winter of 1985 as Oak Bay 1; again didn't sell. May be poached. Needs survey work.
04800	Oak Bay 2	19	Jefferson	19	35	0.02	1.8	5	Surveyed in 1985 by WDFW. Fished 1986-87; 222,136 lbs reported. Post harvest survey 1988; 12 transects.
04850	Olele Point	225	Jefferson	**715**	**2,073**	0.07	2.9	2	Surveyed in 1975 and 1980 by WDFW; 20 transects. Surveyed in 1997 by WDFW; 91 transects. Fished since 1998; 615,569 lbs. reported.
04900	(X)	--	Kitsap	--	--	--	--	11	
04950	(X)	--	Kitsap	--	--	--	--	11	
05000	Admiralty Bay	140	Island	99	198	0.02	--	6/7	Surveyed in 1970 by WDFW; 6 transects. Average geoduck density is low.
05100	Lagoon Point	22	Island	12	24	0.01	--	6/7	Surveyed in 1970 by WDFW; 1 transect. Average geoduck density is low.
05200	Austin	69	Island	163	326	0.05	--	8	Surveyed in 1970 by WDFW; 2 transects.
05300	Double Bluff	73	Island	300	630	0.09	--	8	Surveyed in 1970 by WDFW; 7 transects. Surveyed in 1999 by WDFW; 25 transects within tract. Tract needs additional transects to improve precision of estimate, dig samples (ave. weight of 2.1 lbs. inferred from the nearby Useless Bay tract for the Atlas table estimate), and eelgrass survey to complete pre-fishing survey.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per sq/ft	Average Geoduck Weight (lb)	Bed Status (see footnote)	Comments
05350	Useless Bay	487	Island	668	1,403	0.03	2.1	5/7	Surveyed in 1973 by WDFW as Useless Bay tracts 1-8. Tracts 1-4 and 8 fished 1975-79; 890,000 lbs reported. Resurveyed in 1984 by WDFW; resurveyed in 1989 by WDFW; 82 transects. Portions in south end may have higher densities.
05450	Cultus Bay	230	Island	327	687	0.03	--	6	Surveyed in 1970 and 1975 by WDFW; 10 transects. Surveyed in 1999 by WDFW; 53 transects within tract. No dig samples were taken and the (ave. weight of 2.1 lbs. inferred from the nearby Useless Bay tract for the Atlas table estimate. Average geoduck density is low.
06000	Picnic Point	207	Snohomish	434	649	0.05	1.5	6/7/10	Surveyed in 1970, 1971, 1975, and 1980 by WDFW; 38 transects total for tract #'s 03950 & 06000. Portion closer than 200 yd from shore. Possible pollution due to sewage treatment plant effluent and non-point sources. Number and biomass adjusted to account for Central/North Sound regional boundary line.
06100	Richmond Beach	248	Snohomish and King	94	188	0.02	--	6/7	Surveyed in 1971 by WDFW; 16 transects. Potentially polluted due to Carkeek outfall and other sources. Average geoduck density is low.
06200	Pilot Point	245	Kitsap	163	371	0.02	2.3	6	Surveyed 1977 and 1980 by WDFW; 13 transects. Surveyed in 1999 by WDFW; 39 transects. Area increased in 1999 based on mapping -18 to -70 ft. MLLW contours and extending survey area northerly. The southern 29 acres is productive and is removed from Pilot Point tract and is added to Apple Cove Pt. N. tract. Estimates are based on 1999 survey. The nearshore tract boundary is -20 ft. (MLLW) water depth contour or deeper. Geoduck density in the reconfigured Pilot Point tract is very low.
06250	Apple Cove Point North	301	Kitsap	1,967	3,737	0.15	1.9	2	Surveyed in 1987, 1997, 1999 by WDFW; 145 transects. Area increased in 1999 based on mapping -18 to -70 ft. MLLW contours and adding 29 acres of Pilot Pt. tract to Apple Cove Pt. N. tract. Estimates are based on 1987, 1997, and 1999 surveys, a revised area estimate, and harvest through Dec. 31, 1999. Eelgrass extends to a depth of -23 ft. (MLLW). The nearshore tract boundary is set at -25 ft. (MLLW) or deeper. Fished since 1998; 266,446 lbs. reported.
06300	(X)	--	Kitsap	--	--	--	--	11	

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
06350	Apple Tree Cove	314	Kitsap	2,686	4,835	0.20	1.8	6/7/8/10	Surveyed in 1970, 1975, and 1980 by WDFW; 41 transects. Ferry traffic corridor across tract. Central portion may be polluted due to Kingston sewage effluent and marina. It is estimated that 2,772,000 pounds may be available to harvest outside of the polluted area. Boundaries for the commercial areas of the tract and pre-fishing surveys are needed prior to any harvest.
06400	President Point	455	Kitsap	1,260	2,395	0.06	1.9	1/8	Surveyed in 1977 by WDFW. Portion fished 1977-79 as old 68-acre tract called Jefferson Point; 587,000 lbs reported. Resurveyed by WDFW in 1980; 12 transects. Additional area, 325 acre southern portion, was resurveyed in 1997 by Suquamish Tribe and called "East Indianola"; 11 transects. Estimates from 1980 and 1997 surveys. Needs eelgrass survey and additional transects to meet precision requirement.
06440	Indianola East	263	Kitsap	**1,968**	**3,838**	**0.17**	1.9	8/12	Surveyed in 1975 by WDFW. Portion fished 1976-79 as old Indianola tract; 611,000 lbs reported. Resurveyed in 1978 by WDFW; 14 transects. Resurveyed 1997 by Suquamish Tribe; 80 transects. Tract expanded westerly and southerly into the northern portion of the old Suquamish tract (#06500) and easterly to the boundary of old President Point tract (#06400) in 1997. Tract divided into West (tract #06450) and East (tract #06440) sections in 1999. Additional transects are needed for adequate coverage between existing transect lines and in deeper portions of tract. Eelgrass survey in 1999 by Suquamish Tribe; eelgass extends to -13 ft. (MLLW) depth. Nearshore tract boundary is -18 ft. (MLLW) or deeper. No harvest during January-April due to spawning herring.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per Sq/Ft	Average Geoduck Weight (LB)	Bed Status (See Footnote)	Comments
06450	Indianola West	136	Kitsap	931	2,057	0.16	2.2	2/12	Surveyed in 1975 by WDFW. Portion fished 1976-79 as old Indianola tract; 611,000 lbs reported. Resurveyed in 1978 by WDFW; 14 transects. Resurveyed 1997 by Suquamish Tribe; 80 transects. Tract expanded westerly and southerly into the northern portion of the old Suquamish tract (#06500) and easterly to the boundary of old President Point tract (#06400) in 1997. Tract divided into West (tract #06450) and East (tract #06440) sections in 1999. Approximately 25 acres in most westerly portion of the tract is being commercially fished. Fished since 1998; 65,989 lbs. reported. Eelgrass survey in 1999 by Suquamish Tribe; eelgass extends to -13 ft. (MLLW) depth. Nearshore tract boundary is -18 ft. (MLLW) or deeper. No harvest during January-April due to spawning herring.
06500	Suquamish	42	Kitsap	261	522	0.14	--	6/7/12	This tract is the southern portion of the old Suquamish tract, surveyed in 1980 by WDFW; 5 transects. The northeasterly portion of the old Suquamish tract was surveyed by the Suquamish Tribe in 1997 and is now included as part of the Indianola tract (#06450). Portion may be polluted due to Suquamish sewage effluent. No harvest during January-April due to spawning herring.
06550	Agate Point	75	Kitsap	600	1,080	0.18	1.8	6/7/12	Surveyed in 1980 by WDFW; 7 transects. Possible pollution due to Suquamish sewage effluent. No harvest during January-April due to spawning herring.
06600	Port Madison	135	Kitsap	315	346	0.05	1.1	7/8/12	Surveyed in 1975 by WDFW; 13 transects. Very poor quality geoducks. No harvest during January-April due to spawning herring.

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4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
06800	Agate Pass/ Sandy Hook	138	Kitsap	285	797	0.05	3.1	2/12	This tract includes a portion of former Agate Pass tract (Atlas 1995, 127)which lies in the new Bainbridge Island half of the pass, as well as a portion of old tract 128 (Atlas 1995.) Portions of the old tract, which extended west to the Kitsap side, were surveyed 1968. Fished 1970-1980; 7,579,111 lbs reported. Resurveyed 1981; 28 transects. Surveyed in 1992; 21 transects. Recovered from 0.07 geo/sq ft in 1982 to 0.11 geo/sq ft in 1992. The tract was surveyed in 1994. Thirty-three acres from the Battle Point North tract was added to the Agate Pass/Sandy Hook tract in 1995. The pooled transects, 100 transects, are used to estimate the pre-fishing biomass. Eelgrass survey in 1994 by WDFW. Eelgrass extends to a depth of -17 ft. (MLLW). Shoreward boundary is set at -19 ft. (MLLW) or deeper. Tribal harvest from 9/1/95 to 12/31/99 is 761,107 pounds. Number, biomass, and density estimates from the 1994 survey are adjusted to account for subsequent fishing. No harvest during January-April due to spawning herring.
06850	(X)	--	Kitsap	--	--	--	--	6/11	Possibly polluted by a variety of sources.
06900	Point Bolin	366	Kitsap	590	1,366	0.04	2.3	2/12	This tract is roughly the northern portion of former tract 128 (Atlas 1995, Port Orchard), first surveyed in 1968 by WDFW. Surveyed in 1994 by WDFW; 104 transects. Estimates from 1994 survey adjusted to account for subsequent fishing. Eelgrass surveys 1994. No harvest during January-April due to spawning herring. Harvested 1/1/95-9/1/96; 825,642 lbs.
06910	Keyport	218	Kitsap	103	243	0.01	2.4	6/7/12	This tract is a portion of former tract 128 (Atlas 1995, Port Orchard), first surveyed in 1968 by WDFW. Surveyed in 1994 by WDFW; 31 transects. Estimates in table are from 1994 survey. Partial eelgrass survey 1994. Acreage shown excludes the prohibited zone surrounding the Kitsap County sewage outfall. Average geoduck density is low due to muddy substrate, but portions contain commercial densities. No harvest during January-April due to spawning herring.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
06950	Keyport North	199	Kitsap	--	--	--	--	6/7/12	This tract is part of the former Port Orchard tract 128 (Atlas 1995), surveyed in 1968 by WDFW. Geoducks are present (based on cursory dives during 1994 survey of tract 128.2 (Atlas 1995), but additional further survey work is needed. Needs eelgrass survey. Average geoduck density low due to muddy substrate, but portions contain commercial densities. No harvest during January-April due to spawning herring.
07000	Battle Point North (Manzanita)	723	Kitsap	1,890	4,322	0.06	2.49	4/12	This tract is part of the former Port Orchard tract 128 (Atlas 1995), last surveyed in 1968 by WDFW. Eelgrass survey in 1992 by WDFW. Surveyed in 1994 & 1995 by WDFW; 203 transects. Portion of tract within Manzanita Bay is not part of commercial harvest area. Estimates are from 94 & 95 surveys. No harvest during January-April due to spawning herring.
07100	Battle Point	56	Kitsap	375	787	0.15	2.1	8/10	Surveyed in 1971 and 1980 by WDFW; 8 transects. Majority closer than 200 yd from shore.
07200	Brownsville	45	Kitsap	60	115	0.03	1.9	6/7/10/12	Surveyed in 1971, 1973, and 1980 by WDFW; 16 transects. Portion closer than 200 yd from shore. Very dark-colored geoducks. Possible pollution due to marina. No harvest during January-April due to spawning herring. Average geoduck density is low.
07250	(X)	--	Kitsap	--	--	--	--	11/12	No harvest during January-April due to spawning herring.
07300	(X)	--	Kitsap	--	--	--	--	11	
07350	Illahee North	42	Kitsap	55	93	0.03	1.7	6/7/8	This tract is the northern portion of the old Illahee tract. Surveyed in 1980 by WDFW; 2 transects. Average geoduck density is low.
07360	Illahee	130	Kitsap	1,565	4,225	0.28	2.7	7/8/10	This tract is the southern half of the old Illahee tract and an additional area to the south. Surveyed in 1980 by WDFW; 13 transects. Surveyed in 1997 by the Suquamish Tribe; 20 transects. Portion closer than 200 yards from the mean high water contour. Very dark colored geoducks. State Parks may have restrictions. Needs additional transects in the central portion of the tract.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
07370	Illahee South	113	Kitsap	449	1,515	0.09	3.4	6/7	Surveyed in 1997 by Suquamish Tribe; 25 transects. A southern portion of the tract may be polluted from Bremerton Combined Sewage Overflow discharges. Needs eelgrass survey, additional transects to meet precision requirements, and additional geoduck weight samples.
07400	(X)	--	Kitsap	--	--	--	--	11/12	No harvest during January-April due to spawning herring.
07500	Skiff Point	126	Kitsap	**659**	**1,846**	0.12	2.8	2	Former 1995 Atlas tracts 132 and 133, combined into one tract. Surveyed in 1970, 1975, and 1977 by WDFW; 23 transects. Former tract 133 (Atlas 1995) was fished in 1976-77; 446,651 lbs reported. Resurveyed in 1978 by WDFW; 11 transects. Surveyed in 1995 by WDFW; 41 transects. Estimates in table are from the 1995 survey. Non-Indian harvest from 9/1/96 to 12/31/99 is 429,028 lbs. Tribal harvest from 9/1/96 to 12/31/99 is 593,356 lbs. Numbers, biomass, and density estimates are adjusted to account for fishing. Messenger House sewage outfall zone is immediately south of commercial tract. Eelgrass surveys 1992. Nearshore boundary is -22 ft. (MLLW) due to eelgrass observations to -20 ft. (MLLW).
07550	Murden Cove	222	Kitsap	**579**	**1,216**	0.06	2.1	2	Surveyed 1970, 1973, and 1980. 31 transects. Tract formerly named "Yeomalt." Surveyed in 1995 by WDFW, 68 transects. Estimates are from 1995 survey. Non-Indian harvest from 9/1/96 to 12/31/99 is 355,691 lbs. Tribal harvest from 9/1/96 to 12/31/99 is 140,006 lbs. Number, weight, and density estimates are adjusted to account for fishing. Messenger House sewage outfall zone is immediately north of commercial tract. Eelgrass survey 1992.
07600	(X)	--	Kitsap	--	--	--	--	11	
07650	Tyee Shoal	195	Kitsap	1,556	2,490	0.18	1.6	6/7	Surveyed in 1970 and 1980 by WDFW; 20 transects. Central half of this tract polluted due to Winslow sewage effluent.
07700	Port Blakley	81	Kitsap	258	631	0.07	2.4	4/6/10	Surveyed in 1970 by WDFW; 4 transects. Portion closer than 200 yards from shore. Surveyed in 1996 by WDFW; 35 transects. The northern portion of this tract may not be harvestable due to a ferry lane and harbor contamination.
07750	(X)	--	Kitsap	--	--	--	--	11	
07800	(X)	--	Kitsap	--	--	--	--	11	

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
07850	(X)	--	Kitsap	--	--	--	--	11	
07900	(X)	--	Kitsap	--	--	--	--	6/11	Potentially polluted by Fort Ward STP outfall.
07950	(X)	--	Kitsap	--	--	--	--	11	
08000	(X)	--	Kitsap	--	--	--	--	6/11	Polluted by point sources of pollution.
08050	(X)	--	Kitsap	--	--	--	--	6/11	Polluted by point sources of pollution and/or a marina.
08100	(X)	--	Kitsap	--	--	--	--	6/11	Polluted by point sources of pollution and/or a marina.
08200	Clam Bay	5	Kitsap	48	96	0.22	2.0	6/7	Surveyed in 1980 by WDFW; 4 transects. Possible problems due to DomSea salmon pens.
08250	(X)	--	Kitsap	--	--	--	--	11	
08300	Yukon Harbor	225	Kitsap	414	414	0.04	1.0	6	Surveyed in 1970, 1974, and 1980 by WDFW; 18 transects. Portion closer than 200 yd from shore. Tract is possibly polluted due to Manchester sewage effluent and shoreline sources.
08350	Point Southworth	58	Kitsap	442	619	0.17	1.4	6	Surveyed in 1970, 1980 by WDFW; 14 transects. Tract is possibly polluted due to shoreline sources.
08400	Blake Island North	227	Kitsap	1,700	2,891	0.17	1.7	2/10	Former 1996 Atlas tracts 840 and 845, combined into one tract. Surveyed in 1970 by WDFW. Fished 1976-77; 140,000 lbs reported. Resurveyed in 1978 by WDFW; 31 transects. Surveyed in 1996 by WDFW; 47 transects. Surveyed in 1997 by WDFW; 22 transects. Eelgrass survey in 1996. About 83 acres of this tract are within a state marine park. Portion conditionally approved by Department of Health (DOH). Tract estimate includes both the conditionally approved and approved sections. The nearshore tract boundary is -22 ft. (MLLW) water depth contour or deeper. Tribal harvest from 9/1/97 to 12/31/99 is 32,618 lbs.
08500	East Side Blake Island	22	Kitsap	99	229	0.10	2.3	4/10	Surveyed in 1979 and 1996 by WDFW; 6 transects. Eelgrass survey 1996. The entire tract is within the marine park and is presently unavailable to non-Indian harvest. The area to the north of the commercial harvest area is polluted.
08600	Point Vashon North	51	King	213	511	0.10	2.4	6	Surveyed in 1996 by WDFW; 22 transects. Polluted due to non point sources.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per sq/ft	Average Geoduck Weight (lb)	Bed Status (see footnote)	Comments
08700	Fauntleroy North	141	King	773	1,545	0.13	--	6/7/10	Surveyed in 1971 by WDFW; 18 transects. Tract divided in 1996 by the Central/South Sound Region line to form tracts 09050 & 08700. Estimates are from the 1971 survey. Portion closer than 200 yd from shore. Polluted due to a variety of sources including Metro sewage effluent . Estimates for number, density and biomass were revised from 1996 Atlas due to tract split.
08800	West Point	183	King	1,373	2,746	0.17	--	6	Surveyed in 1970 by WDFW; 8 transects. Polluted due to West Point sewage effluent.
09000	Dolphin Point Recovery Bed	36	King	282	423	0.18	1.5	6/9	Formerly Vashon North. Surveyed in 1975 and 1979 by WDFW. Fished in 1980; 80,000 lbs reported. First post harvest survey in 1983 by WDFW. Fished in 1984; 110,000 lbs reported. Second post harvest survey in 1985 by WDFW; 24 transects. Possible pollution due to non-point residential development. Third post harvest survey in 1993 by WDFW; 24 transects. Average pre-fishing density .19 geo/sq ft.
09050	Fauntleroy South	141	King	773	1,545	0.13	--	6/7/10	Surveyed in 1971 by WDFW; 18 transects. Tract divided by the Central/South Sound Region line to form tracts 08700 & 09050. Estimates are from the 1971 survey. Portion closer than 200 yd from shore. Polluted due to a variety of sources including Metro sewage effluent. Estimates for number, density and biomass were revised from 1996 Atlas due to tract split.
09100	Colvos Pass	95	Kitsap	766	1,532	0.19	--	8/10	Surveyed in 1971 by WDFW; 8 transects. Majority closer than 200 yd from shore.
09200	Olalla	70	Kitsap Pierce	94	188	0.03	--	6/7/10	Surveyed in 1971 by WDFW; 6 transects. Average geoduck density is low. Portion closer than 200 yd from shore.
09300	(X)	--	Pierce	--	--	--	--	11	
09400	Fern Cove Recovery Bed	116	King	972	1,361	0.19	1.4	9	Surveyed in 1970 and 1974 by WDFW. Fished portion as old 25 acre Fern Cove tract 1976-77; 333,368 lbs reported. First post harvest survey in 1978 by WDFW. A 1980 survey added 91 acres to form a new 116 acre tract. Fished 1984; 601,000 lbs. Surveyed 1992; 72 transects. Estimates are from the 1992 survey. Average pre-fishing density .19 geo./sq. ft.
09500	Camp Sealth	4	King	20	36	0.11	1.8	8	Surveyed 1971 and 1980 by WDFW; 6 transects.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
09550	Paradise Cove	50	King	111	200	0.05	1.8	6/8/10	Surveyed 1971 and 1980 by WDFW; 5 transects. Portion closer than 200 yd from shore. A portion is polluted due to failing onsite systems at Spring Beach.
09600	Point Beals	65	King	204	266	0.07	1.3	1/8	Surveyed in 1983 by WDFW. Average pre-fishing density; 0.23 geo./sq.ft. Fished 1985; 549,777 lbs reported. Resurveyed in 1987 by WDFW; 32 transects
09650	(X)	--	King	--	--	--	--	11	
09700	Vashon East Polluted	97	King	690	966	0.16	1.4	6	Surveyed in 1979 by WDFW; 3 transects. Portion polluted due to Vashon sewage effluent.
09750	Vashon East Recovery Bed	53	King	286	487	0.12	1.7	9	Surveyed in 1983 by WDFW. Fished in 1984; 611,000 lbs reported. First post harvest survey in 1985 by WDFW; 30 transects. Second post harvest survey in 1993 by WDFW; 39 transects. Average pre-fishing density; 0.21 geo./sq. ft.
09800	Three Tree Point	103	King	1,781	3,562	0.40	--	6/7/10	Surveyed in 1971 and 1975 by WDFW; 12 transects. Portion closer than 200 yd from shore. Polluted.
09850	(X)	--	King	--	--	--	--	6/11	Polluted due to marina and Des Moines outfall .
09900	Des Moines	26	King	765	1,530	0.68	--	6/7	Surveyed in 1976 by WDFW; 7 transects. Polluted due to marina and Des Moines outfall . Surveys done in January, biomasss may be over-estimated.
09950	(X)	--	King	--	--	--	--	6/11	Potentially polluted due to a variety of pollution sources.
10000	Point Heyer	137	King	1,037	2,282	0.17	2.2	2	Surveyed in 1979 and 1981 by WDFW. Fished 1982; 366,000 lbs reported. Resurveyed 1989; 43 transects. Formerly named "Tramp Harbor." Average pre-fishing density; 0.11 geo./sq.ft. Surveyed in 1998 by WDFW; 66 transects. Tribal harvest from 9/1/98 to 12/31/99; 548 pounds. Non-tribal harvest from 9/1/98 to 12/31/99; 132,070 pounds.
10050	Point Robinson	69	King	574	1,320	0.19	2.3	2	Surveyed in 1979 and 1981 by WDFW. Pre-fishing density 0.11 geo./sq.ft. Fished 1982; 719,000 lbs reported. Resurveyed 1989; 50 transects. Tribal survey 1996; 74 transects. Tribal harvest from Sept. 1, 1996 to Dec. 31, 1999 is 365,976 lbs. Non-tribal harvest from Sept. 1, 1996 to Dec. 31, 1999; 77,470 lbs. Estimates are from 1996 survey which have been adjusted for subsequent fishing.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
10100	Point Robinson E.	43	King	**346**	**935**	**0.18**	2.7	2,10	WDFW survey in 1997 & 1998; 42 transects. Biomass reported is based on 43 acre tract; 21 acres of the 43 acre total is shoreward of the 200 yards from mean high water contour. Non-tribal harvest from Sept. 1, 1998 to Dec. 31, 1999; 45,773 lbs. Estimates are from 1997 & 1998 survey which have been adjusted for subsequent fishing.
10150	Maury Island	149	King	1,399	2798	0.22	--	8/10/12	Surveyed in 1971 by WDFW; 14 transects. Majority closer than 200 yd from shore. No harvest during January-February due to spawning herring.
10250	Rosehilla	220	King	1,495	2,093	0.16	1.4	1/8/12	Surveyed in 1974, 1979, and 1981 by WDFW. Average pre-fishing density; 0.18 geo./sq.ft.. Fished 1982; 892,000 lbs reported. Resurveyed in 1989 by WDFW; 61 transects. No harvest during January-February due to spawning herring.
10300	(X)	--	King	--	--	--	--	6/11/12	No harvest during January-February due to spawning herring. Tract is polluted from failing septic systems.
10350	Neill Point	40	King	525	578	0.17	1.1	7/8/12	Surveyed in 1980 by WDFW; 2 transects. Compact substrate. Poor quality geoducks. No harvest during January-February due to spawning herring.
10400	Dumas Bay	106	King	1,918	3,836	0.42	--	6	Surveyed in 1971 and 1976 by WDFW; 19 transects. Portion closer than 200 yd from shore. Polluted due to marina and Redondo and Lakota sewage outfalls.
10450	(X)	--	Pierce	--	--	--	--	11	
10500	(X)	--	Pierce	--	--	--	--	11	
10600	(X)	--	Pierce	--	--	--	--	11	
10700	(X)	--	Pierce	--	--	--	--	11	
10750	Steilacoom	155	Pierce	1,284	2,568	0.19	--	6	Surveyed in 1971 by WDFW; 14 transects. Polluted by Chambers Creek sewage treatment plant.

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3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
10800	Wollochet Harbor	56	Pierce	520	1,299	0.21	2.5	8	Surveyed in 1969 by WDFW; 9 transects. Eastern portion surveyed in 1998 by Medicine Creek tribes; 51 transects. Estimate is from 1998 survey and only includes hte unpolluted portion of the bed along the eastern shoreline. An eelgrass survey is needed prior ot fishing. The northern portion of this bed is polluted by the Wollochet Harbor sewage treatment plant outfall and marina.
10900	Ketners Point	80	Pierce	304	426	0.09	1.4	7/8	Surveyed in 1979 by WDFW; 7 transects.
10950	Sunny Bay	40	Pierce	244	430	0.14	1.8	1/8	Surveyed in 1979 by WDFW. Average pre-fishing density; 0.22. Fished 1982; 262,000 lbs reported. Resurveyed in 1989 by WDFW; 21 transects.
11000	(X)	--	Pierce	--	--	--	--	11	
11050	(X)	--	Pierce	--	--	--	--	11	
11100	Warren	40	Pierce	197	415	0.11	2.1	7/8/10	Surveyed in 1979 by WDFW; 4 transects. Formerly named "Hale Passage." Portion closer than 200 yd from shore.
11200	Fox Island N	50	Pierce	671	2,281	0.31	3.4	1/8	Surveyed in 1979 by WDFW. Fished 1982; 465,000 lbs reported. Resurveyed 1989; 19 transects. Resurveyed in 1997 by Medicine Creek tribes; 20 transects. Additional transects needed to meet pre-fishing survey precision.
11250	Fox Island	70	Pierce	967	3,673	0.32	3.8	8/10	Surveyed 1971. 7 transects. Resurveyed 1997 by Medicine Creek tribes; 24 transects. Majority closer than 200 yards from shore. Additional transects needed to meet pre-fishing survey precision.
11260	Fox Island S	61	Pierce	905	2,444	0.34	2.7	2/10	Surveyed 1971 as part of old Fox Island tract. Surveyed 1997 by Medicine Creek tribes; 24 transects. Majority closer than 200 yards from shore. Surveyed 1998 by WDFW at pre-fishing intensity; 50 transects. Table reports results of 1997 and 1998 surveys. Tribal harvest from 9/1/98 to 12/31/99; 64,373 pounds.
11300	Green Point	59	Pierce	390	1,092	0.15	2.8	2/10	Surveyed in 1979 by WDFW; 3 transects. Area has been poached. Re-surveyed in 1997 by Medicine Creek tribes; 29 transects. Majority closer than 200 yards from shore. Tribal harvest from 9/1/98 to 12/31/99; 296,639 pounds.

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4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
11350	(X)	--	Pierce	--	--	--	--	6/11	Potentially polluted by nonpoint source pollution.
11400	(X)	--	Pierce	--	--	--	--	11	
11450	Cutts Island	172	Pierce	225	360	0.03	1.6	6	Surveyed in 1974 by WDFW; 16 transects. Average geoduck density is low.
11500	(X)	--	Pierce	--	--	--	--	11	
11550	(X)	--	Pierce	--	--	--	--	11	
11600	Henderson Bay	120	Pierce	654	1,570	0.13	2.4	7	Surveyed in 1978 by WDFW; 3 transects. Muddy substrates.
11700	(X)	--	Pierce	--	--	--	--	11	
11750	Elgin	80	Pierce	38	98	0.01	2.6	5	Surveyed in 1978, 1980, and 1981 by WDFW. Fished 1982-83; 218,000 lbs reported. Resurveyed in 1987 by WDFW; 7 transects.
11800	Minter Creek	48	Pierce	65	156	0.04	2.4	5	Surveyed 1980 and 1981. Fished 1982; 378,000 lbs reported. Resurveyed 1987; 9 transects. Tribal reconnaissance survey in 1996; no geoducks observed
11900	Glen Cove	195	Pierce	168	404	0.02	2.4	5	Surveyed in 1980 and 1981 by WDFW. Formerly named "Carr Inlet." Pre-fishing density 0.06 geo./sq.ft. Fished 1982; 946,000 lbs reported. Resurveyed in 1987 by WDFW; 19 transects. Seeded with geoduck hatchery seed 1987, 1988.
11950	Von Geldern	62	Pierce	23	57	0.01	2.5	5	Surveyed in 1973 by WDFW. Pre-fishing density 0.02 geo./sq.ft. Fished 1976-77; 302,878 lbs reported. Resurveyed in 1978 by WDFW; 9 transects.
12000	(X)	--	Pierce	--	--	--	--	11	
12100	Delano Beach	76	Pierce	138	276	0.05	--	7	Surveyed in 1973-74 by WDFW; 13 transects. Resurveyed northern portion in 1991 by WDFW; 10 transects. Commercial concentrations of geoducks. More survey work is needed to estimate tract size and geoduck populations. Estimates are from 1973-1974 survey data.

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4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
12200	Wyckoff Shoal 1	54	Pierce	70	163	0.03	2.2	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Average density from 1988 survey; 0.10 geo./sq.ft. Fished 6/1/90-12/30/91; 306,703 lbs reported. Used an average density from the 1995 post harvest survey of tracts 12250, 12300, 12400, 12500, and 12650 to estimate biomass.
12250	Wyckoff Shoal 2	137	Pierce	119	320	0.02	2.3	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 589,742 lbs reported. Post-harvest survey in 1995 by WDFW; 19 transects.
12300	Wyckoff Shoal 3	44	Pierce	77	143	0.04	1.9	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 338,698 lbs reported. Post-harvest survey in 1995 by WDFW; 8 transects.
12350	Wyckoff Shoal 4	42	Pierce	73	142	0.04	2.1	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 429,976 lbs reported. Post-harvest survey in 1995 by WDFW; 9 transects.
12400	Wyckoff Shoal 5	65	Pierce	85	160	0.03	2.0	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 617,865 lbs reported. Post-harvest survey in 1995 by WDFW; 10 transects.
12450	Wyckoff Shoal 6	37	Pierce	48	86	0.03	1.7	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 110,356 lbs reported. Used an average density from the 1995 post harvest survey of tracts 12250, 12300, 12400, 12500, and 12650 to estimate poundage

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3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
12500	Wyckoff Shoal 7	38	Pierce	50	132	0.03	2.3	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 464,065 lbs reported. Post-harvest survey in 1995 by WDFW; 5 transects.
12550	Wyckoff Shoal 8	43	Pierce	56	135	0.03	2.3	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 488,088 lbs reported. Used an average density from the 1995 post harvest survey of tracts 12250, 12300, 12400, 12500, and 12650 to estimate poundage
12600	Wyckoff Shoal 9	48	Pierce	63	138	0.03	2.1	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 818,851 lbs reported. Used an average density from the 1995 post harvest survey of tracts 12250, 12300, 12400, 12500, and 12650 to estimate poundage.
12650	Wyckoff Shoal 10	50	Pierce	65	138	0.03	2.4	5	Surveyed in 1969 by WDFW. Fished 1971-80 as part of Pitt Pass tracts 1-6; 2,160,618 lbs reported. Resurveyed in 1988 by WDFW; 252 transects distributed throughout all 10 Wyckoff tracts. Fished 6/1/90-12/30/91; 590,592 lbs reported. Post-harvest survey in 1995 by WDFW; 13 transects.
12700	McNeil Island	106	Pierce	455	865	0.10	1.9	2	Surveyed in 1974 by WDFW; 9 transects. Fished as 34 acre tract called McNeil Island 1977-78; 254,061 lbs reported. Resurveyed in 1980 by WDFW; 9 transects. Surveyed in 1996; 44 transects by WDFW and tribes. Tribal harvest from 9/1/95 to 9/1/97; 44,819 pounds reported. Number, biomass, & density estimates from 1996 survey adjusted for subsequent fishing.
12750	Still Harbor	100	Pierce	448	807	0.10	1.8	8	Surveyed in 1979 by WDFW; 8 transects. About 37 acres east of this tract are polluted due to seal haul-out area. Estimates include only the unpolluted west portion of the tract and are based on 6 transects from the 1979 survey.

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3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
12800	McNeil Island Pen.	57	Pierce	753	1,431	0.30	1.9	6	Surveyed in 1980 by WDFW; 7 transects. Polluted due to penitentiary sewage effluent.
12850	Hogan Point South Recovery Bed	28	Pierce	98	196	0.08	2.0	9	Surveyed in 1983 by WDFW; 13 transects. Fished 1984; 615,000 lbs reported. First post harvest survey in July 1985 by WDFW; 13 transects. Second post harvest survey in July 1996 by WDFW; 13 transects. Average pre-fishing density .19 geo/sq ft.
12900	Hogan Point North Recovery Bed	27	Pierce	98	183	0.08	1.9	9	Surveyed in 1983 by WDFW; 14 transects. Fished 1984; 250,000 lbs reported. First post harvest survey in July 1985 by WDFW; 14 transects. Seeded with hatchery geoduck seed 1987. Second post harvest survey in July 1996 by WDFW; 14 transects. Average pre-fishing density .12 geo/sq ft.
12950	Mahnckes 2-4	92	Pierce	**431**	**1,163**	**0.11**	2.7	2,7	This tract is a combination of Mahnckes tracts 2, 3, and 4. Tracts 3 and 4 were surveyed in 1979. Average pre-fishing density is 0.39 geo./sq.ft. Fished in 1980 as part of Pitt Island tract; 163,000 lbs reported. Resurveyed in 1983. Fished 1984; 1,241,000 lbs reported. Resurveyed 1985; 27 transects. Tract 2 surveyed 1983. Fished 1984; 493,000 lbs reported. Resurveyed 1985; 10 transects. Resurveyed all 3 tracts 1993; 46 transects. Eelgrass survey 1993. Non-Indian harvest from 1/1/95 to 12/31/99; 631,586 lbs reported. Tribal harvest from 9/01/95 to 12/31/99; 532,893 lbs. reported. Number, biomass, and density estimates from 1993 survey adjusted to account for subsequent fishing.
13000	Mahnckes 1	17	Pierce	43	74	0.06	1.7	1/8	Surveyed in 1983 by WDFW; 4 transects. Average pre-fishing density 0.21 geo./sq.ft. Formerly named "Pitt Island." Fished 05/01/88-04/30/89; 125,215 lbs reported. Resurveyed in 1990 by WDFW; 9 transects.
13100	Drayton	183	Pierce	638	1,095	0.08	1.7	5	Surveyed in 1979 by WDFW. Average pre-fishing density 0.23 geo./sq.ft. Fished 1980-81; 495,598 lbs reported. Resurveyed in 1987 by WDFW. Fished 12/01/87-11/30/88 as Drayton 1-6 tracts; 2,541,774 lbs reported. Resurveyed in 1989 by WDFW; 38 transects. Combined 6 tracts back to 1. Present estimate probably too high due to use of a very low show factor (0.33).

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
13200	Otso	108	Pierce	128	226	0.03	1.8	5	Surveyed in 1979 by WDFW; 8 transects. Average pre-fishing density 0.05 geo./sq.ft. Fished 1980-81; 511,134 lbs reported. Resurveyed in 1987 by WDFW. Fished 1988-1989 as Otso 1-4 tracts; 1,083,441 lbs reported. Resurveyed in 1989 by WDFW; 38 transects. Combined 4 tracts back to 1. Seeded with hatchery geoduck seed 1989.
13300	Treble Point	40	Pierce	**305**	**671**	**0.18**	2.2	2	Surveyed in 1980 by WDFW; 7 transects. Average pre-fishing density 0.46 geo./sq.ft. Fished 1984; 517,963 lbs reported. Resurveyed in 1985; 14 transects. Surveyed in 1993 by WDFW; 16 transects. Eelgrass survey in 1993 by WDFW. Fished 1/1/95-5/31/95; 11,559 lbs reported. Tribal survey 1998; 5 transects covering area between -18 ft. (MLLW) contour seaward to 200 yards from MHW contour. Tribal harvest from 9/1/98 to 12/31/99 is 217,532 lbs. Estimates from 1993 and 1998 surveys combined and adjusted to account for fishing.
13400	Thompson Cove	15	Pierce	80	160	0.12	2.0	2	Surveyed in 1992 by WDFW; 16 transects. Fished 1/4/93-5/23/93; 153,112 lbs reported. Fished 1/1/95-5/31/95; 25,297 lbs reported. Estimates from 1992 survey adjusted to account for subsequent fishing.
13500	Oro Bay	140	Pierce	1,080	1,563	0.18	1.5	3	Surveyed in 1991 by WDFW; 10 transects. Surveyed in 1992 by WDFW; 90 transects. Fished 1/4/93-5/23/93; 361,147 lbs reported. Estimates from 1992 survey adjusted to account for subsequent fishing.
13550	Cole Point	17	Pierce	74	148	0.10	--	8	Surveyed in 1991 by WDFW; 3 transects.
13700	DuPont	36	Pierce	77	178	0.05	2.3	8	Surveyed in 1991 by WDFW; 26 transects. Polluted due to ammunition dump and seasonal closures during heavy rainfall events.
13750	McAllister Creek	24	Thurston	48	131	0.05	2.7	8	Surveyed in 1991 by WDFW; 15 transects. Seasonal closures during heavy rain events.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
13800	Nisqually	145	Thurston	315	756	0.05	2.4	2	Surveyed 1973. Portion fished 1975-79; 1,918,000 lbs reported. Resurveyed 1989 and 1991; 78 transects. This tract was fished three times in 1991-1992 under three separate sales as follows: 1) The 145 acre portion shown on the chart was first fished from 8/1/91 to 11/30/91; 455,261 lbs reported, including test fishing. This was the first quota system used in the geoduck fishery. Six quotas of 75,000 lbs each were sold. The SEPA documents covering this fishery extended from Puget Marina to the Thurston-Pierce County line. 2) The second fishery was from 1/1/92 to 3/31/92 when eight quotas of 50,000 lbs each were sold, 411,794 lbs reported, including test fishing. For this fishery, the western boundary was extended northwest about 4000 feet to Dogfish Bight, part of Big Slough tract. The bed offshore of Tolmie State Park was excluded from fishing in this extension. The SEPA documents remained the same for the second and third fisheries. 3) The third fishery was from 4/1/92 to 7/31/92 when 6 quotas of 70,000 pounds were sold. 422,380 lbs reported, test fishery included. The total harvest of all three fisheries was 1,289,435 lbs which is 57% of the estimate for the 145 acre tract. The portion northwest of Tolmie State Park was only lightly fished due to poor geoduck quality when compared to the original 145 acre tract. Tribal harvest from 9/1/96 to 12/31/99 is 174,527 lbs. reported. Figures in table have been adjusted for subsequent fishing.
13850	Big Slough/ Sandy Point	185	Thurston	1,092	2,511	0.14	2.3	2	Big Slough portion surveyed 1973. Fished 1979-1980; 312,000 lbs reported. Resurveyed 1991; 63 transects. Portion of Big Slough fished in 1992 (see Nisqually tract comments). State Parks has withdrawn about 10 acres. Sandy Pt portion surveyed in 1984; fished 1986; 147,022 lbs reported. Sandy Pt. resurveyed 1991; 12 transects. Portions combined into one tract fished January 4-May 23, 1993; 245,648 lbs reported. May have seasonal closures. Combined tract surveyed by WDFW in 1998; 56 transects. Non-Indian harvest from Sept. 1, 1998 to Dec. 31, 1999 is 359,718 lbs. reported. Estimates in table are from 1998 survey and have been adjusted for subsequent fishing.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
13900	Dogfish	31	Thurston	89	151	0.06	1.7	5	Surveyed in 1984 by WDFW. Average pre-fishing density .31 geo/sq ft. Fished 1986; 772,033 lbs reported. First post harvest survey in 1987 by WDFW; 15 transects. Second post harvest survey in 1996 by WDFW; 15 transects. Seeded with hatchery geoduck seed in 1987. Tract may have been fished during test harvest of Big Slough/Sandy Point. Pounds reported from 1998 test harvest have been attributed to Big Slough/Sandy Point tract.
14000	Puget Recovery Bed	21	Thurston	141	254	0.14	1.8	9	Surveyed in 1984 by WDFW. Fished 1986; 682,333 lbs reported. First post harvest survey in 1987 by WDFW; 9 transects. Second post harvest survey in 1996 by WDFW; 9 transects. Average pre-fishing density .36 geo/sq ft.
14100	Mill Bight Recovery Bed	8	Thurston	89	178	0.25	2.0	6/9	Surveyed in 1984 by WDFW. Fished 1985-86; 249,760 lbs reported. First post harvest survey in 1986 by WDFW; 9 transects. Second post harvest survey in 1996 by WDFW; 9 transects. Possible pollution due to Zittel's and Johnson's marinas. Average pre-fishing density .52 geo/sq ft.
14200	Baird Cove	32	Thurston	113	237	0.08	2.1	1/6/7	Surveyed in 1984 by WDFW. Fished 1986; 550,554 lbs reported. Resurveyed in 1986 by WDFW; 14 transects. A portion is possibly polluted due to Johnson's marina.
14300	Taylor Bay	12	Pierce	167	340	0.33	2.0	6	Surveyed in 1984 by WDFW; 17 transects. Resurveyed in 1989 by WDFW; 16 transects. Polluted due to Taylor Bay Estates sewage effluent.
14400	Whitemans Cove	27	Pierce	79	170	0.07	2.2	1/8	Surveyed in 1979 and 1982 by WDFW. Average pre-fishing density 0.16 geo./sq.ft. Fished 1983; 25,000 lbs reported. Resurveyed 1984. Fished 1985; 531,348 lbs reported. Resurveyed 1986; 24 transects.
14500	Herron Island South	20	Pierce	202	363	0.23	1.8	8/10	Surveyed in 1979 by WDFW; 8 transects. Portion closer than 200 ft from shore.
14600	(X)	--	Pierce	--	--	--	--	11	
14650	Herron Island 12	14	Pierce	13	25	0.02	1.9	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; 170,363 lbs reported. Resurveyed in 1991 by WDFW; 8 transects.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
14700	Herron Island 11	10	Pierce	209	392	0.48	1.9	8	Didn't sell with rest of Herron Island tracts.
14750	Herron Island 10	28	Pierce	116	209	0.10	1.8	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; 424,777 lbs reported. Resurveyed in 1991 by WDFW; 11 transects.
14800	Herron Island 9	15	Pierce	156	283	0.24	1.8	8	Didn't sell with rest of Herron Island tracts.
14850	Herron Island 8	45	Pierce	27	50	0.01	1.8	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; 327,351 lbs reported. Resurveyed in 1991 by WDFW; 15 transects.
14900	Herron Island 7	14	Pierce	341	638	0.56	1.9	8	Didn't sell with rest of Herron Island tracts.
14950	Herron Island 6	55	Pierce	31	51	0.01	1.6	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; 221,729 lbs reported. Resurveyed in 1991 by WDFW; 9 transects.
15000	Herron Island 5	20	Pierce	6	13	0.01	2.1	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; combined reported catch for Herron Island tracts 3,4, & 5 was 286,751 lbs. Resurveyed in 1991 by WDFW; 6 transects.
15050	Herron Island 4	30	Pierce	7	14	0.01	2.2	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; combined reported catch for Herron Island tracts 3,4, & 5 was 286,751 lbs. Resurveyed in 1991 by WDFW; 5 transects.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
15100	Herron Island 3	19	Pierce	4	9	0.01	2.2	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; combined reported catch for Herron Island tracts 3,4, & 5 was 286,751 lbs. Resurveyed in 1991 by WDFW; 7 transects.
15150	Herron Island 2	22	Pierce	4	10	0.00	2.4	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; 110,244 lbs. Resurveyed in 1991 by WDFW; 6 transects.
15200	Herron Island 1	62	Pierce	22	48	0.01	2.2	5	Surveyed in 1973, 1976, and 1978 by WDFW. Fished 1978-83 as part of old Herron Island Tracts 1-5; 2,809,000 lbs reported. These tracts added to new ground divided into 12 tracts. Surveyed in 1988 by WDFW; 159 transects. Fished 10/01/89-04/01/91; 231,040 lbs. Resurveyed in 1991 by WDFW; 30 transects
15250	(X)	--	Pierce	--	--	--	--	11	
15300	Windy Bluff	150	Pierce	786	2,280	0.12	2.9	7/8	Surveyed in 1978 and 1979 by WDFW; 10 transects. Muddy substrates, heavily poached.
15350	(X)	--	Pierce/ Mason	--	--	--	--	11	
15400	(X)	--	Mason	--	--	--	--	11	The northern portion may be within a shellfish conditional area.
15450	Stretch Island	40	Mason	78	111	0.04	1.4	7/8	Surveyed in 1969 and 1973 by WDFW; 11 transects. Small, poor quality geoducks.
15500	Dougall Polluted	104	Mason	1,793	4,661	0.40	2.6	6	Surveyed in 1979 and 1982 by WDFW; 15 transects. Polluted due to Hartstene Point development sewage effluent.
15550	Dougall Point 2 Recovery Bed	20	Mason	62	180	0.07	2.9	9	Surveyed in 1982 by WDFW. Fished 1983; 349,000 lbs reported. Resurveyed in 1984 by WDFW; 8 transects. Resurveyed in 1994 by WDFW; 8 transects. Average geoduck density increased from 0.04 geo/sq ft in 1984 to 0.07 geo/sq ft in 1994. Average pre-fishing density .21 geo/sq.ft

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
15600	Dougall Point 1A Recovery Bed	26	Mason	90	260	0.08	2.9	9	Surveyed in 1982 by WDFW. Fished 1983; 140,000 lbs reported. Resurveyed in 1984 by WDFW. Fished 1985; 350,581 lbs reported. Resurveyed in 1986 by WDFW; 14 transects. Resurveyed in 1994 by WDFW; 14 transects. Average geoduck density increased from 0.04 geo/sq ft in 1986 to 0.08 geo/sq ft in 1994. Average pre-fishing density .18 geo/sq.ft
15650	Fudge Point Recovery Bed	70	Mason	184	459	0.06	2.5	9	Surveyed in 1982 by WDFW. Fished 1983; 574,000 lbs reported. Resurveyed 1984; 22 transects. Resurveyed in 1994 by WDFW; 22 transects. Average geoduck density increased from 0.04 geo/sq ft in 1984 to 0.06 geo/sq ft in 1994. Average pre-fishing density is 0.16 geo./sq.ft.
15700	McMicken Island North	11	Mason	18	49	0.04	2.7	1/8	Surveyed in 1982 by WDFW. Fished 1983; 287,000 lbs reported. Resurveyed 1984. Fished 1985; 136,487 lbs. reported. Resurveyed in 1986 by WDFW; 7 transects. Average pre-fishing density is 0.35 geo./sq.ft.
15750	McMicken Island North A	49	Mason	599	1,498	0.28	2.5	7/8	Surveyed in 1976 and 1982 by WDFW; 8 transects.
15800	McMicken Island South	31	Mason	34	75	0.03	2.2	5	Surveyed in 1982 by WDFW; 23 transects. Fished 1984-85; 553,481 lbs reported. Resurveyed 1986; 17 transects. State Parks has withdrawn the northern portion of this tract. Average pre-fishing density estimate is 0.23 geo./sq.ft.
15850	Reno	34	Mason	48	105	0.03	2.2	5	Surveyed in 1982 by WDFW. Fished 1983; 370,000 lbs reported. Resurveyed in 1984 and 1986 by WDFW; 12 transects. Average pre-fishing density estimate is 0.15 geo./sq. ft.
15900	Buffington	74	Mason	45	94	0.03	2.1	5	Surveyed in 1977 by WDFW; 12 transects. Average pre-fishing density is 0.37 geo./sq.ft. Fished 1980-81 as part of old 101 acre tract called Buffington Lagoon; 537,000 lbs reported. Resurveyed in 1986 by WDFW. Divided into 3 tracts called Buffington 1, 2, & 3. Fished 05/01/87-04/30/88; 1,811,000 lbs reported. Resurveyed in 1989 by WDFW; 17 transects. Combined back into 1 tract.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
15950	Wilson	30	Mason	23	62	0.02	2.7	5	Surveyed in 1979 by WDFW. Fished 1980-81 as part of old 65 acre tract called Wilson Point; 456,000 lbs reported. Resurveyed in 1986 by WDFW. Divided into 2 tracts called Wilson 1 and 2. Fished 05/01/87-04/30/88; 575,205 lbs reported. Resurveyed in 1989 by WDFW; 3 transects. Combined back into 1 tract.
16000	(X)	--	Mason	--	--	--	--	11	
16100	(X)	--	Thurston	--	--	--	--	11	
16150	Henderson Inlet	213	Thurston	1,010	2,020	0.11	--	7/8/10	Surveyed in 1969 and 1979 by WDFW; 18 transects. Muddy substrate. Portion closer than 200 yd from shore.
16200	(X)	--	Thurston	--	--	--	--	11	
16250	Henderson 2 Recovery Bed	40	Thurston	288	634	0.17	2.2	9	Surveyed in 1979 by WDFW. Fished 1980-81 as part of old Dickenson Point tract; 566,000 lbs reported. Resurveyed in 1984 by WDFW. Fished 1985 as Henderson 2; 1,111,679 lbs reported. Resurveyed in 1986 by WDFW; 25 transects. Survey ed in 1992 by WDFW; 38 transects. Combined average pre-fishing density for tracts 16250 and 16300 is .25 geo/sq.ft
16300	Henderson 1A Recovery Bed	19	Thurston	75	173	0.09	2.3	9	Surveyed in 1979 by WDFW . Fished 1980-81 as part of old Dickenson Point tract; 566,000 lbs reported. Resurveyed in 1984 by WDFW. Fished 1985; 329,900 lbs reported. Resurveyed in 1986 by WDFW; 12 transects. Surveyed in 1992 by WDFW; 14 transects. Combined average pre-fishing density for tracts 16250 and 16300 is .25 geo/sq.ft
16350	(X)	--	Mason/ Thurston	--	--	--	--	11	
16400	(X)	--	Mason/ Thurston	--	--	--	--	11	
16450	Peale Passage	180	Mason	675	1,485	0.08	2.2	7/8/10	Surveyed in 1969 and 1973 by WDFW; 18 transects. Muddy substrate. Portion closer than 200 yd from shore.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per sq/ft	Average Geoduck Weight (lb)	Bed Status (see footnote)	Comments
16500	Dover Point	24	Thurston	167	451	0.16	2.7	1/7/8	Surveyed in 1979 and 1981 by WDFW; 19 transects. Average pre-fishing density estimate is 0.19 geo./sq.ft. Originally tract was divided into two tracts named Dover Point and Dana Passage, each 12 acres. Tract fished as one tract called Dover Point 1981; 135,000 lbs reported. Resurveyed in 1989 by WDFW; 16 transects.
16550	(X)	--	Thurston	--	--	--	--	11	
16600	Budd Inlet 1	53	Thurston	150	442	0.07	2.9	6	Surveyed in 1988 by WDFW; 22 transects. Average pre-fishing density is 0.04 geo./sq.ft. Potential pollution from Boston Harbor sewage outfall.
16650	Budd Inlet 2	53	Thurston	15	47	0.01	3.2	5/6	Surveyed in 1988 by WDFW. Average pre-fishing density is 0.04 geo./sq.ft. Fished 04/01/89-04/30/90; 404,114 lbs reported. Resurveyed in 1990 by WDFW; 8 transects. Potential pollution from Boston Harbor sewage outfall.
16700	Budd Inlet 3	68	Thurston	14	45	0.00	3.2	5/6	Surveyed in 1988 by WDFW. Average pre-fishing density is 0.04 geo./sq.ft. Fished 04/01/89-04/30/90; 252,637 lbs reported. Resurveyed in 1990 by WDFW; 11 transects. Potential pollution from Boston Harbor sewage outfall.
16750	Budd Inlet 4	51	Thurston	14	41	0.01	3.0	5/6	Surveyed in 1988 by WDFW. Average pre-fishing density is 0.04 geo./sq.ft. Fished 04/01/89-04/30/90; 146,955 lbs reported. Resurveyed in 1990 by WDFW; 7 transects. Potential pollution from Boston Harbor sewage outfall.
16800	Budd Inlet 5	34	Thurston	18	50	0.01	2.8	5/6	Surveyed in 1988 by WDFW. Average pre-fishing density is 0.04 geo./sq.ft. Fished 12/01/88-11/30/89; 72,687 lbs reported. Resurveyed in 1990 by WDFW; 5 transects. Potential pollution from Boston Harbor sewage outfall.
16850	(X)	--	Thurston	--	--	--	--	6/11	Potential pollution from Boston Harbor sewage outfall.
16870	(X)	--	Thurston	--	--	--	--	11	Potentially polluted due to a variety of pollution sources.
16900	Big Hunter Recovery Bed	93	Thurston	241	747	0.06	3.1	9	Surveyed in 1979 and 1981 by WDFW. Fished 1981; 2,680,000 lbs reported. Resurveyed in 1982 by WDFW; 25 transects. Resurveyed in 1993 by WDFW. Average density of population recovered from 0.03 geo/sq ft in 1982 to 0.06 geo/sq ft in 1993. Average pre-fishing density 0.17 geo/sq.ft

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per sq/ft	Average Geoduck Weight (lb)	Bed Status (see footnote)	Comments
16950	Weist Windmill	53	Thurston	140	449	0.06	3.2	1/8	Surveyed in 1979 and 1981 by WDFW. Fished 1982; 437,000 lbs reported. Resurveyed in 1982 by WDFW; 17 transects. Average pre-fishing density 0.25 geo/sq.ft
17000	Rignall	9	Thurston	42	104	0.11	2.5	1/8	Surveyed in 1979 and 1981 by WDFW. Fished 1982; 116,000 lbs reported. Resurveyed in 1989 by WDFW; 5 transects.
17050	(X)	--	Thurston	--	--	--	--	11	
17100	Cooper Point	5	Thurston	45	134	0.20	3.0	1/8	Surveyed in 1979 and 1981 by WDFW. Fished 1981; 196,000 lbs reported. Resurveyed in 1989 by WDFW; 11 transects.
17150	Eld Inlet East	54	Thurston	59	172	0.03	2.9	5	Surveyed in 1969 by WDFW; 3 transects. Surveyed in 1996 by WDFW; 31 transects. Approximately 27 acres of this tract are shoreward of the 200 yards from MHW contour. Non-Indian harvest from Sept. 1, 1997 to August 31, 1998 is 134,845 lbs. reported. Tribal harvest from Sept. 1, 1998 to December 31, 1999 is 109,947 lbs. reported.
17200	Eld Inlet West	98	Thurston	125	414	0.03	3.3	5	Surveyed in 1989 by WDFW; 26 transects. Surveyed in 1996 by WDFW; 34 transects. Estimates from 1989 and 1996 data combined. Approximately 35 acres of this tract are shoreward of the 200 yards from MHW contour. Non-Indian harvest from Sept. 1, 1997 to August 31, 1998 is 352,364 lbs. reported. Tribal harvest from Sept. 1, 1998 to December 31, 1999 is 59,118 lbs. reported.
17300	(X)	--	Thurston	--	--	--	--	11	
17400	Salom Point	461	Mason	318	884	0.02	2.8	6	Surveyed in 1979 by WDFW; 5 transects. Arcadia 1-4 and Salom Point tracts combined and surveyed in 1995 by WDFW; 95 transects. Arcadia 1-4 and Salom Point tracts divided in 1997 Atlas. Used 1995 survey; 52 transects for data in table. Average weight inferred from 1987 survey samples.
17410	Arcadia 5	99	Mason	129	349	0.03	2.7	6/7/10/12	Surveyed in 1969 and 1979 by WDFW; 6 transects. Most of tract shallower than 18 feet. No harvest during January-April due to spawning herring.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
17420	Arcadia 1	28	Mason	35	98	0.02	2.8	2	Surveyed in 1973 by WDFW. Fished 1974-79 as part of old Arcadia tract; 3,149,000 lbs reported from entire area. Resurveyed in 1987 by WDFW; 29 transects. Seeded with geoduck hatchery seed 1985, 1986, 1987. Combined Arcadia 1-4, and Salom Point tracts and surveyed in 1995 by WDFW; 95 transects. Arcadia 1-4 and Salom Point tracts divided along 1987 tract boundary lines. Tribal harvest on Arcadia 1-4 from 9/1/95 to 8/31/98 is 469,072 lbs. reported. Tribal harvest on Arcadia 1 from 9/1/98 to 12/31/99 is 482 lbs. reported. Number, biomass, and density estimates from 1995 survey adjusted to account for subsequent fishing.
17430	Arcadia 2	26	Mason	118	319	0.10	2.7	2	Surveyed in 1973 by WDFW. Fished 1974-79 as part of old Arcadia tract; 3,149,000 lbs reported from entire area. Resurveyed in 1987 by WDFW; 29 transects. Seeded with geoduck hatchery seed 1985, 1986, 1987. Combined Arcadia 1-4, and Salom Point tracts and surveyed in 1995 by WDFW; 95 transects. Arcadia 1-4 and Salom Point tracts divided along 1987 tract boundary lines. Tribal harvest on Arcadia 1-4 from 9/1/95 to 8/31/98 is 421,260 lbs. reported. Tribal harvest on Arcadia 2 from 9/1/98 to 12/31/99 is 9,040 lbs. reported. Number, biomass, and density estimates from 1995 survey adjusted to account for subsequent fishing.
17440	Arcadia 3	55	Mason	116	300	0.05	2.6	2	Surveyed in 1973 by WDFW. Fished 1974-79 as part of old Arcadia tract; 3,149,000 lbs reported from entire area. Resurveyed in 1987 by WDFW; 29 transects. Seeded with geoduck hatchery seed 1985, 1986, 1987. Combined Arcadia 1-4, and Salom Point tracts and surveyed in 1995 by WDFW; 95 transects. Arcadia 1-4 and Salom Point tracts divided along 1987 tract boundary lines. Tribal harvest on Arcadia 1-4 from 9/1/95 to 8/31/98 is 435,303 lbs. reported. Tribal harvest on Arcadia 3 from 9/1/98 to 12/31/99 is 75,623 lbs. reported. Number, biomass, and density estimates from 1995 survey adjusted to account for subsequent fishing.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
17450	Arcadia 4	118	Mason	147	383	0.03	2.6	2	Surveyed in 1973 by WDFW. Fished 1974-79 as part of old Arcadia tract; 3,149,000 lbs reported from entire area. Resurveyed in 1987 by WDFW; 29 transects. Seeded with geoduck hatchery seed 1985, 1986, 1987. Combined Arcadia 1-4, and Salom Point tracts and surveyed in 1995 by WDFW; 95 transects. Arcadia 1-4 and Salom Point tracts divided along 1987 tract boundary lines. Tribal harvest on Arcadia 1-4 from 9/1/95 to 8/31/97 is 395,555 lbs. reported. Tribal harvest on Arcadia 4 from 9/1/98 to 12/31/99 is 154,783 lbs. reported. Number, biomass, and density estimates from 1995 survey adjusted to account for subsequent fishing.
17500	Steamboat 3	48	Thurston	30	91	0.01	3.1	5	Surveyed in 1979 by WDFW. Fished 1980-1981 as part of Steamboat tract; 581,000 lbs reported from entire area. Resurveyed in 1987 by WDFW. Fished 04/01/89-04/30/90; 522,368 lbs reported. Resurveyed in 1990 by WDFW; 28 transects.
17550	Steamboat 2	48	Thurston	61	208	0.04	3.4	5	Surveyed in 1979 by WDFW. Fished 1980-81 as part of Steamboat tract; 581,000 lbs reported from entire area. Resurveyed in 1987 by WDFW. Fished 04/01/89-04/30/90; 342,005 reported. Resurveyed in 1990 by WDFW; 6 transects.
17600	Steamboat 1	26	Thurston	67	194	0.06	2.9	5	Surveyed in 1979 by WDFW. Fished 1980-81 as part of Steamboat tract; 581,000 lbs reported from entire area. Resurveyed in 1987 by WDFW. Fished 04/01/89-04/30/90; 388,782 lbs reported. Resurveyed in 1990 by WDFW; 5 transects.
17650	(X)	—	Thurston	—	—	—	—	6/11/12	No harvest during January-April due to spawning herring. A portion of this tract may be polluted by the Carlyon Beach sewage treatment outfall.
17700	Windy Point	310	Mason	26	53	0.00	–	6	Surveyed in 1969 by WDFW; 4 transects. Surveyed in 1998 by WDFW; 22 transects. Average geoduck density is low. Puget Sound average geoduck weight of 2.0 lbs. used to estimate biomass.
17800	Steamboat 4	18	Thurston	10	28	0.01	2.9	5	Surveyed in 1979 by WDFW. Fished 1980-1981 as part of old Steamboat tract; 581,000 lbs reported from entire area. Resurveyed in 1987 by WDFW. Fished 04/01/89-04/30/90; 207,233 lbs reported. Resurveyed in 1990 by WDFW; 4 transects.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per sq/ft	Average Geoduck Weight (lb)	Bed Status (see footnote)	Comments
17900	Totten Inlet	107	Thurston	23	46	0.01	--	6/12	Surveyed in 1969 by WDFW; 5 transects. Surveyed in 1998 by WDFW; 22 transects. Average geoduck density is low. Puget Sound average geoduck weight of 2.0 lbs. used to estimate biomass. No harvest during January-April due to spawning herring.
19000	(X)	--	Jefferson	--	--	--	--	11	
19100	Snake Rock	16	Jefferson	28	56	0.04	--	6/7	Surveyed in 1986 as part of Port Ludlow sewage treatment expansion; 22 transects. Possible pollution due to Port Ludlow sewage effluent.
19150	Port Ludlow	10	Jefferson	167	334	0.38	--	6	Surveyed by private consultant as part of Port Ludlow sewage treatment expansion. Polluted due to Port Ludlow sewage effluent.
19200	Colvos Rocks	23	Jefferson	20	40	0.03	--	7/8	Surveyed 1986 as part of Port Ludlow sewage treatment expansion. May have seasonal closures due to STP. Average geoduck density is low. Fished in 1998 as part of Colvos Rocks E. and Tala Pt. tracts.
19300	Colvos Rocks East	125	Jefferson	188	268	0.03	1.4	2	Surveyed in 1989, 1991, 1993 by WDFW; 57 transects. Average geoduck density is low. Portions have commercial densities. Fished in 1998 as part of Tala Pt. tract.
19350	Tala Point	72	Jefferson	**191**	**229**	**0.06**	1.2	2	Surveyed in 1989 and 1993 by WDFW; 53 transects. Estimates in table are from 1989 & 1993 data. Eelgrass survey in 1993. Non-Indian harvest from Sept. 1, 1996 to Dec 31, 1999; 359,240 pounds. Number, biomass, and density estimates adjusted to account for subsequent fishing.
19400	Tala Point South	38	Jefferson	**587**	**763**	**0.35**	1.3	2	Surveyed in 1980 by WDFW; 7 transects. Surveyed in 1993 by WDFW; 31 transects. Estimates in table are from 1993 survey. Eelgrass survey in 1993. Non-Indian harvest from Sept. 1, 1996 to Dec. 31, 1999; 7,944 pounds. Number, biomass, and density estimates adjusted to account for subsequent fishing.
19450	Point Hannon	120	Jefferson	**303**	**485**	**0.06**	1.6	2	Surveyed in 1976 and 1980 by WDFW; 12 transects. Surveyed in 1991 by WDFW; 86 transects. Estimates are from 1991 survey. Eelgrass survey 1993. Non-Indian harvest from Sept. 1, 1996 to Dec. 31, 1999; 331,601 pounds. Number, biomass, and density adjusted to account for subsequent fishing.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

Tract No.	Tract Name	Size (Acres)	County	Estimated Geoduck Population: Number of Geoducks (x1000)	Pounds of Geoducks (x1000)	Ave. Number of Geoducks per sq/ft	Average Geoduck Weight (lb)	Bed Status (see footnote)	Comments
19550	Foulweather Bluff	40	Kitsap	306	459	0.18	1.5	8	Surveyed in 1970 and 1980 by WDFW; 7 transects.
19600	(X)	--	Kitsap	--	--	--	--	11	
19650	Foulweather	64	Kitsap	677	1,016	0.24	1.5	7/8/12	Surveyed in 1986 by WDFW; 33 transects. Good numbers of geoducks, but difficult to dig due to gravel, except 6 acres in north end. Needs more work. No harvest during January-April due to spawning herring.
19700	Foulweather 1	39	Kitsap	168	272	0.10	1.6	1/8/12	Survey in 1970 and 1973 by WDFW. Fished 1977-79 under the name of Foulweather Bluff. 635,672 lbs reported. Resurveyed in 1986 by WDFW; 15 transects. No harvest during January-April due to spawning herring.
19750	Foulweather 2	19	Kitsap	356	769	0.43	2.2	8/12	Surveyed in 1986 by WDFW; 12 transects. No harvest during January-April due to spawning herring.
19900	Coon Bay 1-4	99	Kitsap	952	2,570	0.22	2.7	1/4/12	Coon Bay 1 tract (39 acres) surveyed in 1970 & 1973 by WDFW. Fished 1977-79 under the name of Coon Bay South; 839,141 lbs reported. Surveyed with Coon Bay 2-4 (15,12,13 acres respectively) in 1986 by WDFW; 51 transects. Coon Bay tracts (tract #'s 19800 - 19950) combined and surveyed by PNPTC in 1997 to -70 ft. (MLLW) depth contour; 38 transects. Combined tract estimate is from PNPTC survey. Deepest occurrence of eelgrass is -14 ft (MLLW). No harvest during January-April due to spawning herring.
20000	Port Gamble	264	Kitsap	6,606	9,909	0.57	1.5	2/12	Surveyed in 1975 by WDFW. Portion fished with tract 19850, 1976-78; 1,821,000 lbs reported. Resurveyed in 1986 by WDFW; 80 transects. Closure period due to spawning herring. Surveyed in 1996 by PNPTC; 96 transects. Estimate based on 1996 survey. The nearshore tract boundary is -20 ft. (MLLW) water depth contour or deeper. Tribal harvest from Sept. 1, 1996 to Dec. 31, 1999; 886,503 lbs. reported. Number, biomass, & density estimates adjusted to account for subsequent fishing.
20050	Port Gamble Polluted	90	Kitsap	1,748	2,622	0.45	1.5	1/6/8/12	Surveyed in 1975 by WDFW. Portion fished with tract 19850, 1976-78; 1,821,000 lbs reported. Resurveyed in 1978 by WDFW; 8 transects. Portion of this tract is in the Port Gamble STP closure zone. No harvest during January-April due to spawning herring.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
20100	Port Gamble Inside	185	Kitsap	969	3,586	0.12	3.7	2/10/12	Surveyed 1968. 5 transects. Portions closer than 200 yd from shore. Excessive mud substrate. Closure due to spawning herring. Surveyed 1995 by PNPTC; 26 transects. Tribal harvest from 1/1/95 to 9/1/97; 115,478 pounds. Tribal harvest from 9/1/98 to 12/31/99 is 75,515 lbs. reported. Number, biomass, & density estimates from 1995 survey adjusted for subsequent fishing.
20200	Hood Head East	37	Jefferson	521	902	0.32	1.7	2	Surveyed in 1989, 1993 by WDFW; 24 transects. Eelgrass surveys 1993. Tract area between -18 (MLLW) water depth contour and the 200 yard from MHW contour added to tract in 1999. The portion of the tract available for state harvest is approximately 18 acres seaward of the 200 yard from MHW contour. Number, biomass, and density estimates revised based tract reconfiguration and harvest. Additional eelgrass survey work is needed in northern portion of tract prior to harvest. Non-Indian harvest from 9/1/98 to 12/31/99 is 12,697 lbs. reported.
20250	Hood Head South	40	Jefferson	509	917	0.29	1.8	2	Surveyed in 1989, 1991 by WDFW; 50 transects. Eelgrass surveys 1993. Non-Indian harvest from 9/1/96 to 12/31/99; 253,169 lbs. reported. Number, biomass, & density estimates adjusted for subsequent fishing.
20300	Sisters/Shine	459	Jefferson	2,114	4,228	0.11	2.0	2/12	Surveyed in 1968, 1975, and 1978 by WDFW. Shine tract fished 1977-79; 482,000 lbs reported. Sisters tract fished 1979-80; 409,602 lbs reported. Surveyed 1989; 57 transects on combined tracts. Tracts re-mapped by DNR and suveyed in 1998 by WDFW; 125 transects. Estimates are from 1998 survey. Eelgrass extends to -18 ft. (MLLW) water depth contour. The nearshore boundary of the tract is the -20 ft. (MLLW) water depth contour. No harvest during January-April due to spawning herring. Non-Indian harvest from 9/1/98 to 12/31/99; 541,008 lbs. reported.
20400	Case Shoal	75	Jefferson	195	312	0.06	1.6	1/8	Surveyed in 1978 by WDFW. Fished 1979-80; 248,000 lbs reported. Resurveyed in 1989 by WDFW; 34 transects.

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1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
20450	Case Shoal South	182	Jefferson	534	748	0.07	1.4	2	Case Shoal 1, 2, and 3 were surveyed in 1989 by WDFW as part of 155 acre tract called Case Shoal South. Contains portion of tract called Case Shoal West. Resurveyed in 1990 by WDFW; 123 transects. Fished 6/1/93-12/31/93; 752,358 lbs reported. Fished 6/1/94-12/31/94; 294,190 lbs reported. Tribal harvest from 9/195 to 8/31/98, 211,007 pounds. Number, biomass, & density estimates from 1990 survey adjusted to account for subsequent fishing.
20500	South Point	69	Jefferson	90	158	0.03	1.8	6	Surveyed in 1986 by WDFW; 34 transects. Average geoduck density is low.
20550	Thorndyke	147	Jefferson	731	1,029	0.11	1.3	3	Surveyed in 1968 by WDFW. Fished 1970-80 as part of old Thorndyke 1, 2, & 3; 2,784,000 lbs reported. Resurveyed in 1986 and 1990 as Thorndyke 1-4; 119 transects. Tracts combined into one; fished 8/13/92-12/31/92; 629,933 lbs reported. Tract fished 6/1/93-12/31/93; 435,070 lbs reported. Tract fished 1/3/94-12/31/94; 736,588 lbs reported. Estimates from 1990 survey adjusted to account for subsequent fishing.
20600	Hood Canal Bridge	46	Kitsap	843	1,264	0.42	1.5	6/8/10/12	Surveyed in 1980 by WDFW; 8 transects. Tract is closer than 200 yd from shore. Possible pollution problems from non-point sources. No harvest during January-April due to spawning herring.
20650	Bridge	63	Kitsap	588	855	0.21	1.5	4/10/12	Surveyed in 1986 by WDFW; 12 transects. Surveyed in 1995 by WDFW; 25 transects. Estimates in table are from 1995 survey. About half of the tract is closer than 200 yds. from MHW. No harvest during January-April due to spawning herring.
20700	Lofall	170	Kitsap	526	757	0.07	1.4	2/12	Surveyed in 1986 & 1990 by WDFW as Lofall 1 & 2. Lofall 1 & 2 were combined into one tract which equaled 170 acres, excluding portion withdrawn by Parks adjacent to Kitsap Memorial Park. Eelgrass survey in 1993. Fished 1/3/94-5/31/94; 465,124 lbs reported. No harvest during January-April due to spawning herring. Tribal harvest from 1/1/95 to 9/1/96; 14, 263 lbs. reported. Number, biomass, & density estimates from 1990 survey adjusted to account for subsequent fishing.

All reported catches before August 1, 1991 have been reduced 10% for water loss.

1. Fished in past.
2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
20750	Vinland	100	Kitsap	849	1,266	0.19	1.5	3	Surveyed in 1986 by WDFW as Vinland 1-4; 50 transects. Combined into one tract for fishing. Eelgrass survey in 1993. Tract was fished 1/3/94-5/31/94; 436,580 lbs reported. All values in table refer to 100 acre portion that is pollution free. South of tract may be polluted due to toxic discharges. Estimates from 1986 survey adjusted to account for subsequent fishing.
20800	Brown Point	31	Jefferson	322	408	0.24	1.3	3	Surveyed in 1986 and 1990 by WDFW; 44 transects. Fished 8/13/92; 141,891 lbs reported. Fished 6/1/93-12/31/93; 103,506 lbs reported. Fished 6/1/94-12/ 31/94; 50,485 lbs reported. Estimates from 1990 survey adjusted to account for subsequent fishing.
20850	(X)	--	Jefferson	--	--	--	--	11	
20900	Brown Point South	20	Jefferson	68	86	0.08	1.4	3	Surveyed in 1990 by WDFW; 29 transects. Fished 8/13/92-12/31/92; 145,322 lbs reported. Fished 6/1/93-12/31/93; 51,280 lbs reported. Estimates from 1990 survey adjusted to account for subsequent fishing.
21000	Hazel Point	179	Jefferson	1,483	3,410	0.19	2.3	2	This tract is a combination of Toandos Peninsula (2100), Hazel Point (2105) and x-bed (2095). Refer to 1996 Geoduck Atlas for tract locations. Toandos Peninsula was surveyed in 1971 by WDFW; 2 transects. Hazel Point was surveyed in 1971 by WDFW; 7 transects. All three tracts were surveyed in 1996 as one tract by PNPTC; 97 transects. Majority of tract closer than 200 yd from shore. Estimates are from 1996 survey. Tribal harvest from 9/1/96 to 12/31/99; 466,713 lbs. reported. Number, biomass, & density estimates from 1996 survey adjusted to account for subsequent fishing.
21100	(X)	--	Kitsap	--	--	--	--	6/11	Potential pollution due to toxic discharges.
21150	Bangor-Trident	116	Kitsap	465	651	0.09	1.4	7	Surveyed in 1971 by WDFW; 8 transects. Lies within US Naval Trident submarine base.
21200	(X)	--	Kitsap	--	--	--	--	11	
21250	(X)	--	Kitsap	--	--	--	--	11	
21300	(X)	--	Kitsap	--	--	--	--	11	
21350	Olympic View	20	Kitsap	229	435	0.26	1.9	8	Surveyed in 1971 by WDFW; 2 transects.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION				BED STATUS (SEE FOOT-NOTE)	COMMENTS
				NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)		
21450	Warrenville (Big Beef)	421	Kitsap	1,606	2,924	0.09	1.8	2/7	Combination of tracts 2140 (Atlas 1996), Big Beef 2145 (Atlas 1996), and 2145 Warrenville (Atlas 1996) Surveyed tract 2145 (Atlas 1996) in 1968, 1973, & 1976; 21 transects. Surveyed tract 2140 (Atlas 1996) in 1968, 1970, & 1973, 9 transects. Fished former tract 2140 (Atlas 1996) in 1975-79; 355,000 lbs reported. Surveyed in 1996 by WDFW; 102 transects. Acreage and biomass revisions are based on 1996 survey. Needs eelgrass survey. Tribal harvest from 9/1/98 to 12/31/99 is 254,477 lbs. reported.
21500	Oak Head	54	Jefferson	25	50	0.01	--	6/7/10	Surveyed in 1971 by WDFW; 5 transects. Majority closer than 200 yards from shore. Average geoduck density is low.
21550	Zelatched Point	40	Jefferson	6	12	0.00	--	6/7	Surveyed in Nov 1993 by WDFW; 7 transects, geoducks were not showing well, needs more survey work. Average geoduck density is low.
21600	Tabook Point	80	Jefferson	16	32	0.00	--	6/7	Surveyed in Nov 1993 by WFDW; 12 transects; geoducks were not showing well, needs more survey work. Average geoduck density is low.
21650	Camp Discovery	288	Jefferson	233	466	0.02	--	6	Surveyed in Nov 1993 by WDFW; 29 transects; geoducks were not showing well. PNPTC survey 1998; 12 transects; confirmed average geoduck density is low.
21700	North Dabob	50	Jefferson	22	44	0.01	--	6	Surveyed in Nov 1993 by WDFW; 9 transects; geoducks were not showing well. PNPTC survey 1997; 26 transects. Average geoduck density is low.
21750	Broadspit	24	Jefferson	43	86	0.04	--	7/8	Surveyed in 1971 and Nov 1993 by WDFW; 3 transects; geoducks were not showing well, needs more survey work.
21800	Red Bluff	40	Jefferson	68	135	0.03	--	7/8	Surveyed in 1971 and Nov 1993 by WDFW; 8 transects. Resurveyed in 1997 by PNPTC; 24 transects. Biomass based on 1997 survey and Puget Sound average weight of 2.0 lbs. Additional survey work needed to estimate mean weight, determine depth of eelgrass, and improve precision of pre-fishing estimate.
21850	(X)	--	Jefferson	--	--	--	--	11	
21900	(X)	--	Jefferson	--	--	--	--	11	
21950	(X)	--	Jefferson	--	--	--	--	11/12	No harvest during February-April due to spawning herring.

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2. Commercial bed presently being fished.
3. Commercial bed fished in past, may need post harvest survey when fishing completed.
4. Commercial bed, ready to fish.
5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

ATLAS OF MAJOR GEODUCK TRACTS OF PUGET SOUND; APRIL 20, 2000

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOTNOTE)	COMMENTS
22000	(X)	--	Jefferson	--	--	--	--	11/12	No harvest during February-April due to spawning herring.
22050	(X)	--	Jefferson	--	--	--	--	11	
22100	Cedric's Beach	10	Jefferson	13	26	0.03	--	7/8/12	Surveyed in February 1994 by WDFW; 4 transects; geoducks were not showing well, needs more survey work. No harvest during February-April due to spawning herring. Average geoduck density is low.
22150	Jackson Cove	50	Jefferson	6	12	0.00	--	6	Surveyed in Nov 1993 by WDFW; 12 transects; geoducks were not showing well. No harvest during February-April due to spawning herring. PNPTC survey 1998; 4 transects; confirmed average geoduck density is low.
22200	Wawa Point	80	Jefferson	8	16	0.00	--	6	Surveyed in Nov 1993 by WDFW; 12 transects; geoducks were not showing well. No harvest during February-April due to spawning herring. PNPTC survey 1998; 3 transects; confirmed average geoduck density is low.
22250	Dosewallips	15	Jefferson	38	75	0.06	2.0	6	Surveyed in 1971 and 1974 by WDFW; 10 transects. Surveyed in 1998 by WDFW; 20 transects. Productive area for geoducks is a narrow band along a steep slope of the river delta. Puget Sound average geoduck weight of 2.0 pounds used to estimate biomass. Adjacent to state park. Portion possibly closed to shellfish harvest due to seal pollution.
22300	Seabeck	35	Kitsap	15	30	0.01	--	6/7	Surveyed in 1970 by WDFW; 2 transects. Surveyed in 1998 by PNPTC; 8 transects; portions may contain commercial densities. A portion may be within a commercial closure zone. Needs mapping and additional survey work.
22350	Stavis Bay	6	Kitsap	17	38	0.07	2.2	8	Surveyed in 1971 and 1978 by WDFW; 8 transects.
22400	Hoodpoint	52	Kitsap	45	90	0.01	--	6/7	Surveyed in 1971 by WDFW; 3 transects. Average geoduck density is low.
22450	Tekiu Point	13	Kitsap	25	59	0.04	2.4	8	Surveyed in 1971 and 1985 by WDFW; 12 transects.
22500	(X)	--	Kitsap	--	--	--	--	11	

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5. Commercial bed fished in past, fished out.
6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
9. Bed included in recovery study.
10. Statutory or land use restriction, noted in comments.
11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (X1000)	POUNDS OF GEODUCKS (X1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
22550	Anderson Cove Recovery Bed	65	Kitsap	65	117	0.02	1.8	9	Surveyed in 1985 by WDFW; 47 transects. Fished 1985-86; 157,557 lbs reported. Resurveyed in 1988 by WDFW; 14 transects. Surveyed in 1992; 32 transects. Estimates are from 1992 survey. Average density of population recovered from 0.01 geo/sq ft in 1988 to 0.02 geo/sq ft in 1992. Average pre-fishing density .07 geo/sq ft
22600	(X)	--	Kitsap	--	--	--	--	11	
22650	Quatsap Point	20	Jefferson	42	85	0.05	2.0	4	Surveyed in 1971 and 1981 by WDFW; 8 transects. Surveyed in 1998 by WDFW; 13 transects. Puget Sound average geoduck weight of 2.0 lbs. used to estimate biomass. Approximately half of tract area is shoreward of 200 yds. from MHW contour.
22700	Duckabush	9	Jefferson	92	184	0.23	2.0	6	Surveyed in 1971 by WDFW; 8 transects. Surveyed in 1998 by WDFW; 7 transects. Puget Sound average geoduck weight of 2.0 lbs. used to estimate biomass. Geoduck density is higher in shallow portions of this area. Portion possibly closed to shellfish harvest due to seal pollution.
22750	(X)	--	Jefferson	--	--	--	--	11	
22800	Triton Head South	58	Kitsap	49	98	0.02	--	6/7/10	Surveyed in 1971 by WDFW; 2 transects. Majority closer than 200 yards from shore. Average geoduck density is low.
22850	Hamma Hamma	14	Mason	20	39	0.03	2.0	4	Surveyed in 1971 and 1974 by WDFW; 9 transects. Surveyed in 1998 by WDFW; 7 transects. Approximately half of tract area is shoreward of 200 yds. from MHW contour.
22900	Ayock Point	5	Mason	39	72	0.17	1.9	6	Surveyed in 1971 and 1981 by WDFW; 8 transects. Productive zone has a very steep slope; non-commercial.
22950	(X)	--	Mason	--	--	--	--	11	
23000	Chinom Point	72	Kitsap	28	56	0.01	--	6/7/10	Surveyed in 1971 by WDFW; 3 transects. Majority closer than 200 yards from shore. Average geoduck density is low.
23100	Lilliwaup	58	Mason	95	190	0.04	--	8/10	Surveyed in 1971 by WDFW; 2 transects. Majority closer than 200 yards from shore.
23150	(X)	--	Mason	--	--	--	--	11	

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6. Non-commercial bed for reasons given in comments.
7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
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11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

TRACT NO.	TRACT NAME	SIZE (ACRES)	COUNTY	ESTIMATED GEODUCK POPULATION: NUMBER OF GEODUCKS (x1000)	POUNDS OF GEODUCKS (x1000)	AVE. NUMBER OF GEODUCKS PER SQ/FT	AVERAGE GEODUCK WEIGHT (LB)	BED STATUS (SEE FOOT-NOTE)	COMMENTS
23200	Hoodsport	58	Mason	30	60	0.02	--	6/7/10	Surveyed in 1971 by WDFW; 2 transects. Majority closer than 200 yards from shore. Average geoduck density is low. Possibly polluted due to nonpoint pollution and a marina.
23250	Annas Bay	62	Mason	184	368	0.02	--	6/7	Surveyed in 1971 by WDFW; 2 transects. Needs more survey work. Average geoduck density is low. Occassional emergency closures may occur due to flooding of the Skokomish River.
23400	(X)	--	Mason	--	--	--	--	11	
23450	(X)	--	Mason	--	--	--	--	11	
23500	Musqueti Point	10	Mason	13	23	0.03	--	6/7	Surveyed in 1971 and 1978 by WDFW; 6 transects. Average geoduck density is low.
23550	Tahuya	82	Mason	0	0	0.00	--	6	Surveyed in 1971 and 1978 by WDFW; 11 transects. Surveyed in 1996 by WDFW; 52 transects. Average geoduck density is low. Geoducks observed occasionally on fewer than half of the transects; non-commercial.
23600	Union	66	Mason	187	374	0.06	--	6/8/10	Surveyed in 1971 by WDFW; 3 transects. Majority closer than 200 yards from shore. Portions of this tract may be in the Prohibited area of the Alderbrook STP outfall and a marina.
23700	Union East	62	Mason	74	148	0.03	--	6/7/10	Surveyed in 1971 by WDFW; 3 transects. Majority closer than 200 yards from shore. Average geoduck density is low.
23800	Hood Canal South End	62	Mason	33	66	0.01	--	6/7/10/12	Surveyed in 1971 by WDFW; 2 transects. Majority closer than 200 yards from shore. No harvest during January-March due to spawning herring. Average geoduck density is low. Portions of this tract may be in the Prohibited areas of the state park pumpout, wading pool discharge, and marina area.
24000	Sisters Point	62	Mason	184	368	0.07	--	8/10	Surveyed in 1971 by WDFW; 2 transects. Majority closer than 200 yards from shore.

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7. Status unclear, needs more survey work.
8. Needs pre-fishing survey.
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11. X-bed, has not been surveyed.
12. Harvest restriction to protect spawning herring.

Appendix 2

The time between successive crops (recovery time) of subtidal geoducks (*Panopea abrupta*) in Puget Sound, Washington

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March 2000

INTRODUCTION

The annual Total Allowable Catch (TAC) for the commercial geoduck clam (*Panopea abrupta*) fishery in Washington is calculated by applying an annual harvest rate to estimates of the commercially harvestable biomass. The annual harvest rate was based on a Ricker yield-per-recruit (YPR) model until 1997, when managers began using an age-based equilibrium yield model, which framed its predictions in terms of spawning-biomass-per-recruit (SPR). The original YPR model resulted in a constant-catch strategy with the annual harvest rate equal to 2% of the unfished biomass ($2\%B_0$). The current harvest rate strategy ($F_{40\%}$) is predicted to preserve 40% of the unfished spawning biomass, resulting in a constant harvest rate of 2.7% of the current commercial biomass ($2.7\%B_t$). Details of the stock assessment procedure and equilibrium yield model are contained in Bradbury and Tagart (2000) and Bradbury *et al.* (1997). TACs are calculated annually for each of six management regions in Washington. The entire regional TAC is harvested in a few discrete commercial tracts each year, and the TAC in subsequent years is taken from other tracts. The fishing strategy is therefore a form of periodic (rotational) harvest. Once fished, a tract is not re-fished until surveys demonstrate that it has returned to its pre-fishing levels of geoduck density and biomass.

Both the former YPR and current equilibrium yield models belong to the group of so-called "structural" models. Structural models represent fish populations in some simplified way which nevertheless captures their essential dynamics. In such models, variables usually include estimates of natural mortality, growth, sexual maturity, and fishery selectivity. A major practical advantage of structural models is that they allow managers to make predictions about yield and spawning biomass for a wide range of harvest rates *before* actually applying those harvest rates.

Structural models also have many disadvantages, however. All the variables are estimated with some degree of error, and many rely on untested assumptions. For example, both the YPR and equilibrium yield models for geoducks rely on catch-curve estimates of natural mortality, which in turn rely on untested assumptions regarding constant recruitment and constant mortality across all age classes. Growth and mortality parameters are estimated from unfished populations, even though it is acknowledged that they may be affected by fishing. More importantly, nothing is known about the stock-recruitment relationship for geoducks. Consequently, both models have assumed that recruitment is independent of the stock across all stock levels. Structural models are also necessarily limited in the number of variables they include. The geoduck models, for example, do not take into account environmental or climactic changes which may affect geoduck populations.

An alternative to structural modeling is empirical modeling. Empirical (or heuristic) models ignore the underlying factors which influence population dynamics, focusing instead on how a fished population fluctuates over time. This *post hoc* approach precludes the use of empirical models prior to fishing, or in the early stages of a fishery. But empirical models have great utility as a test of structural models. Once a fishery is underway, for example, empirically observed changes in the population can be compared with the predictions of a structural model as a method of "ground truthing." Moreover, the predictions from an empirical model implicitly include all the factors which influenced the population during the observation period (including recruitment, environmental and climactic changes).

Here we use a simple empirical model to estimate the time required for commercially fished geoduck populations to recover to their pre-fishing levels. We then compare these empirical results with the harvest rate predictions of structural models used to manage the geoduck fishery.

METHODS

Geoduck densities in 15 separate commercial tracts were estimated from diver surveys before fishing, shortly after fishing, and again after several years of no fishing. A recovery rate for each tract was estimated from the difference in density between the first post-fishing survey and the second post-fishing survey. The time for fished geoduck populations to recover to their pre-fishing density was then estimated, assuming that the observed recovery rate would remain the same until pre-fishing density was attained.

The commercial tracts involved in this study are shown in Figure 1. Study tracts were chosen opportunistically (rather than randomly or systematically) from among the many surveyed and commercially-fished tracts in Puget Sound. Study tracts were chosen which met all the following criteria: 1) Tracts which included adequate positioning information for each transect; 2) Tracts where the first post-fishing survey was made within one year of the end of fishing; 3) Tracts where the pre-fishing and first post-fishing survey occurred during the seasonal period of high "show" factor (Goodwin 1977), and; 4) Tracts which were roughly representative of the geographic spread of commercial tracts in Puget Sound. Tracts which met these four criteria were included in the study and scheduled for a second post-fishing survey.

Standardized geoduck survey methods used throughout the study are described in detail by Bradbury *et al.* (1997). In these surveys, two divers count geoduck siphon "shows" within a series of 900 ft^2 strip transects. One exception in this study to the established survey procedures is that density estimates were not adjusted with a "show" factor. "Show plots" used in many of the pre-fishing surveys were no longer physically intact or considered reliable at the time of the second post-fishing surveys. For this reason, only the unadjusted diver counts of geoducks for each transect were used in estimating density. These density estimates therefore underestimate the actual geoduck density, but are assumed to be comparable as relative indices of abundance from survey to survey. The "show" factor for a given site varies seasonally (Goodwin 1977). To reduce possible survey-to-survey variability due to the show factor, we attempted to synchronize the seasonal timing of post-harvest surveys. For example, if the first post-harvest survey at a particular site was conducted during the first week of June, we attempted to conduct the second post-fishing survey during the first week of June.

Pre-fishing surveys were completed from 1972-85, depending on the tract. Most of the pre-fishing surveys were conducted in 1983-85. The second post-fishing surveys were conducted during the spring and summer of 1992, 1993, and 1994.

The number of geoducks observed within each transect was recorded for the pre-fishing and post-fishing surveys at each tract. The data were log-normalized, and the log-transformed data were analyzed with a student's t-test to determine if statistically significant differences in the mean density existed between surveys on a given tract All t-tests were carried out at the $\alpha = 0.05$ significance level and assumed unequal variances. At each site, the first t-test was performed to determine if significant differences existed between the pre-fishing mean density and the first post-fishing mean density. We assumed that any significant differences between the two densities were due entirely to commercial fishing. Given the low natural mortality rate of geoducks ($M = 0.0226$, Bradbury *et al.* 1997) and the fact that the first post-fishing survey was conducted within a year of the end of fishing, this is a reasonable assumption. A second t-test was then performed comparing the mean densities of the first and second post-fishing surveys. Significant differences in this case would be due to post-fishing recruitment.

The observed rate of recovery (in terms of density) from the first post-fishing survey to the second post-fishing survey was calculated as:

$$r = \Delta t \,/\, (D_2 - D_1) \qquad (1)$$

where r = rate of recovery
Δt = time (in yr) between first post-fishing and second post-fishing surveys
D_1 = mean density of first post-fishing survey

D_2 = mean density of second post-fishing survey

Assuming that r remains constant, the projected time to recover from the observed post-fishing density to the pre-fishing density is given by:

$$T = r\,(D_0 - D_1) \qquad (2)$$

where T = time (in yr) to recovery from the observed post-fishing density
D_0 = mean density of the pre-fishing survey

Commercial tracts are never fished down completely (i.e., until density = 0), and the observed post-fishing density differs for each tract, depending on both the initial density and the tract-specific harvest rate. To standardize recovery time over all the tracts, we calculated the time for each tract to recover to pre-fishing density if *all* harvestable geoducks had been removed from the tract:

$$T_{100\%} = r\,D_0 \qquad (3)$$

where $T_{100\%}$ = time (in yr) to recovery assuming complete removal of all geoducks

The mean $T_{100\%}$ for all tracts was calculated and used to predict optimum annual harvest rates which corresponded to the constant-catch and constant harvest rate strategies currently used in managing the geoduck fishery. Fishery models frame their predictions in terms of biomass, whereas the recovery study data are in terms of density. Geoducks, however, grow rapidly and reach asymptotic between the ages of 10 - 20 yr (Goodwin 1976; Bradbury *et al.* 1997). If mean recovery times were < 10 - 20 yr, then density would likely underestimate biomass to some degree. But as long as mean recovery time > 20 yr, the difference between density and biomass is negligible. Thus, for the following comparisons, we use the two terms interchangeably. Likewise, many of the comparisons between model predictions and results of the recovery study treat total biomass and spawning biomass as the same thing. Given the young age at which geoducks become sexually mature, the difference between total and spawning biomass will be less than 1% (Bradbury *et al.* 1997) and can therefore be ignored.

The optimum constant-catch harvest rate (harvest rate as a proportion of *unfished*, "virgin" biomass B_0) is given by:

$$\mu_{constant\text{-}catch} = 1 / T_{100\%} + 1 \qquad (4)$$

The effects of a constant harvest rate strategy (μ, or harvest rate as a proportion of *current* biomass B_t) were explored using two simple biomass dynamics models. The first model assumed linear recovery after fishing, while the second model assumed logistic recovery after fishing. Both models were initiated in year 0 by setting unfished biomass B_0 equal to 10,000 units, divided into 100 "tracts," each tract containing a biomass $b_{x,0}$ of 100 units. In the first year of fishing ($t = 1$), the annual catch was equal to μB_0. In both models, biomass on tracts beginning with the first tract were reduced in sequence until a total catch equal to μB_0 had been removed. In the linear model, it was possible to reduce tracts to zero biomass; the logistic model required at least a small amount of residual biomass to remain on a fished tract following harvest.

Following the first year's harvest ($t = 2$), biomass was constrained to remain stable (i.e., $b_{x,2} = 100$) on all unfished tracts, but was allowed to recover on fished tracts according to either a linear or logistic model. In the linear model, biomass recovered each year by a constant amount equal to $b_{x,t}\,(1/T_{100\%})$ until tract biomass again reached the unfished biomass level of 100. In the logistic model, biomass on a fished tract b_x in each subsequent year was given by:

$$b_{x,t+1} = b_{x,t} + r\,b_{x,t}\,(1 - b_{x,t}\,/\,K) \tag{5}$$

where K is the carrying capacity (the unfished tract biomass, in this example 100 units per tract) and r is the intrinsic rate of population growth in the logistic model. We chose r by iteration, assigning it the value which allowed tract biomass to recover to $K = 100$ after a time span equal to the projected recovery time ($T_{100\%}$).

In each subsequent year t, total current biomass B_t was calculated for both models as the sum of biomass on all 100 tracts, both fished and unfished. Catch in year t was equal to μB_t, and fishing was continued in this way until a new equilibrium was reached.

These two models were used to explore the relationship between recovery time, harvest rate, and biomass. First, the mean recovery time ($T_{100\%}$) for all tracts and the current annual harvest rate ($\mu = 0.027$) were used as input, and each model was run until B_t reached a stable fishing equilibrium (i.e., when $B_t = B_{t-1}$). The ratio of equilibrium biomass to unfished biomass ($B_t\,/\,B_0$) could then be compared to yield model predictions under the current $F_{40\%}$ management strategy ($B_t\,/\,B_0 = 0.40$). Second, the two models were used to search (using different trial values of μ) for the harvest rate μ which produced a fishing equilibrium corresponding to the current management target ($F_{40\%}$).

RESULTS

The average geoduck density (number/900 ft^2 transect) decreased following fishing at all 15 study tracts, then increased during the recovery (i.e., no-fishing) period (Table 1). The decrease following fishing averaged 72% and ranged from a low of 19% to a high of 95% (Table 2). Students t-tests showed that 14 of the 15 decreases were statistically significant (Table 3). At Agate Pass, the first post-fishing survey did not indicate a statistically-significant decrease compared to the pre-fishing survey. In other words, our surveys were not able to demonstrate any effect of fishing at Agate Pass. At five of the tracts, the increases in density between the first and second post-fishing surveys were not statistically significant (Table 3). Reported catches at each of the 15 tracts are given in Table 4.

The average estimated time to recover to pre-fishing density assuming complete removal of all geoducks ($T_{100\%}$) was 41.56 yr when data from all 15 tracts were included (Table 2). When the analysis was restricted to only those tracts with significantly different means (n = 9), the mean recovery time was 39.39 yr, ranging from a low of 11 yr at Indian Island to a high of 73 yr at Dougall Point 2 (Table 2).

Using mean $T_{100\%}$ = 39 yr, the optimum constant-catch harvest rate was equal to 1 / (39+1) = 0.025 (Eq. 4). Thus, under the assumption of constant recovery rate and an average 39-yr "turnover time" for tracts, an annual harvest rate of $2.5\%B_0$ is expected to be the maximum which would allow for continuous rotation of tracts. During the years when Washington managers used a constant-catch strategy, an annual harvest rate of $2\%B_0$ was in effect.

With mean $T_{100\%}$ = 39 yr, the proportion of biomass being replaced each year for the linear model was equal to $1/T_{100\%}$ = 0.0256. Thus, a tract originally containing 100 units of biomass would recover 2.56 units each year following harvest, recovering all 100 units 39 years after fishing. Using this value in the linear model resulted in a fishing equilibrium at $B_t / B_0 = 0.65$ following 47 yr of fishing at the current harvest rate $\mu = 0.027$ (Figure 2). Thus, the linear model when applied to recovery study data suggests that an annual harvest rate of 2.7% will eventually reduce spawning biomass to 65% of its unfished level, rather than the 40% predicted by the equilibrium yield model and $F_{40\%}$ strategy. Figure 2 shows, however, that prior to reaching equilibrium, biomass dipped to $B_t / B_0 = 0.63$ at 34 yr.

For the logistic model, the intrinsic rate of population growth (r) which allowed complete recovery of tract biomass after 39 yr was found by iteration to be 0.2675 (Figure 3). The biomass trajectory using the logistic model was similar to those predicted by the linear model (Figure 2), but biomass dipped to $B_t / B_0 = 0.62$ at 24 yr before reaching equilibrium at $B_t / B_0 =$ 0.64 in 49 yr.

We next searched for the harvest rate which, assuming an average recovery time of 39 yr, reduced B_t / B_0 to no less than 0.40. Because the logistic model always allowed biomass to dip below the predictions of the linear model, only the logistic model was used in this analysis. The annual harvest rate which dropped B_t / B_0 to 0.40 (i.e., corresponding to the $F_{40\%}$ strategy) was 0.057, or $5.7\%B_t$ (Figure 4). This harvest rate eventually produced a long-term fishing equilibrium at $B_t / B_0 = 0.45$ after 48 yr (Figure 4).

DISCUSSION

The preliminary results of this study confirm that post-fishing recruitment does occur on commercial geoduck tracts. The preliminary results also confirm earlier hypotheses (Goodwin and Shaul 1984) that recruitment (and consequently the time required for recovery) varies considerably from tract to tract. Thus, under the rotational harvest strategy, certain tracts are expected to be re-harvested more often than others. Under such a management strategy, the optimum sustainable harvest rate is one which corresponds with the average recovery time in a management region. Based on these preliminary post-fishing data, the average recovery time is 39 yr, suggesting that model-based harvest rates (both the former constant-catch 2%B_0 and the current constant harvest rate 2.7%B_t) are somewhat conservative (i.e., sub-optimal). It is noteworthy, however, that harvest rates based on recovery time fall short of model-based harvest rates which are predicted to maximize yield-per-recruit (7.5%B_t ; Bradbury and Tagart 2000; Bradbury *et al.* 1997). One possible reason is that commercial fishing may adversely affect recruitment, a hypothesis which agrees with the earlier experimental results of Goodwin and Shaul (1984).

The recovery data presented here should be considered preliminary, for the obvious reason that recovery times have been projected from just two post-fishing data points, both fairly early in the recovery of most tracts.

We recommend that the recovery study be continued in the future. Additional post-fishing data points at all tracts will more reliably define both the form and the time required for recovery. Additional surveys may also require some adjustment in the underlying assumption of a population at long-term equilibrium. There is some indication in the preliminary results that density on some tracts (e.g., Fern Cove) may increase to a level above the pre-fishing density. Conversely, it is also possible that some tracts may fail to reach pre-fishing densities, perhaps due to niche-filling by other organisms following the geoduck fishery (e.g., horse clams).

Managers should also consider expanding the recovery study in the future to include other fished tracts. One of the problems in extrapolating results of the present study is that the study tracts were selected neither randomly or systematically. This resulted in "clumping" of study tracts in some areas, and the absence of study tracts in other areas. From a practical standpoint it is impossible to select sites randomly or systematically, but some attempt could be made to expand the number of study tracts and fill in geographic gaps wherever possible. Additional study tracts would increase the reliability of the study, and possibly allow for the analysis of spatial patterns in recovery.

The recovery study should continue to serve as an independent, empirical test of predictions based on structural models of the geoduck population. Empirical models of this sort rely on fewer assumptions than structural models, and their predictions reflect the net effects of *all* the variables which may affect a population. These include natural environmental and climactic changes, competition with other species, the stock-recruitment relationship, even poaching and pollution. Empirical models do not imply causality, and therefore do not shed light on the underlying biological processes affecting populations. But as Fogarty (1989) points out, it is often possible to make more accurate predictions with empirical models than with structural models. As more data are gathered on the recovery tracts, managers may choose to replace yield-model harvest rates with empirically-based harvest rates. For the moment, however, structural and empirical models of the geoduck population are likely to play complementary roles in fisheries management.

Acknowledgements

The authors would like to thank Bob Sizemore, Don Rothaus, Amy Leitman, and the late Dwight Herren for their participation in post-harvest dive surveys. Dwight Herren performed the statistical tests, and Michael Ulrich created the site map. Don Flora and Dr. José (Lobo) Orensanz contributed their considerable modeling and biological expertise, and critiqued earlier drafts.

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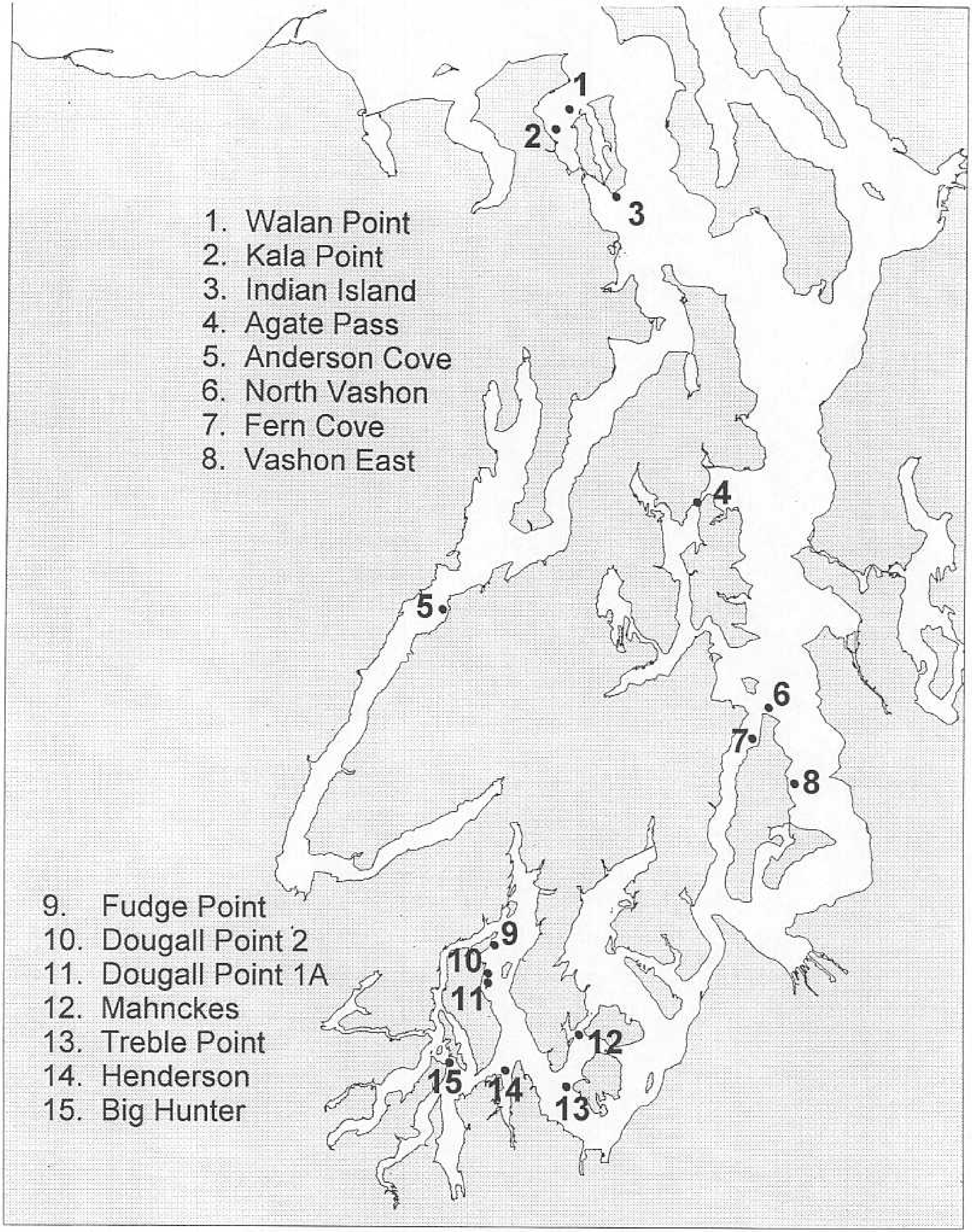
Figure 1. Commercial geoduck tracts surveyed in the recovery study.



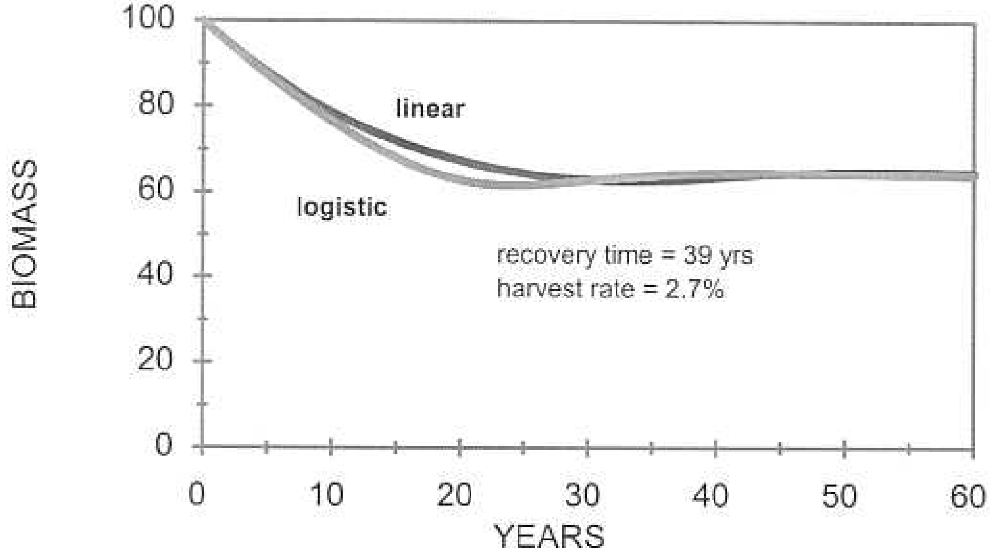


Figure 2. The effect of a constant harvest rate strategy ($\mu = 0.027$) on geoduck biomass, assuming an average recovery time to pre-fishing density on individual tracts of 39 yr. Predictions were calculated using linear and logistic recovery models described in the text.

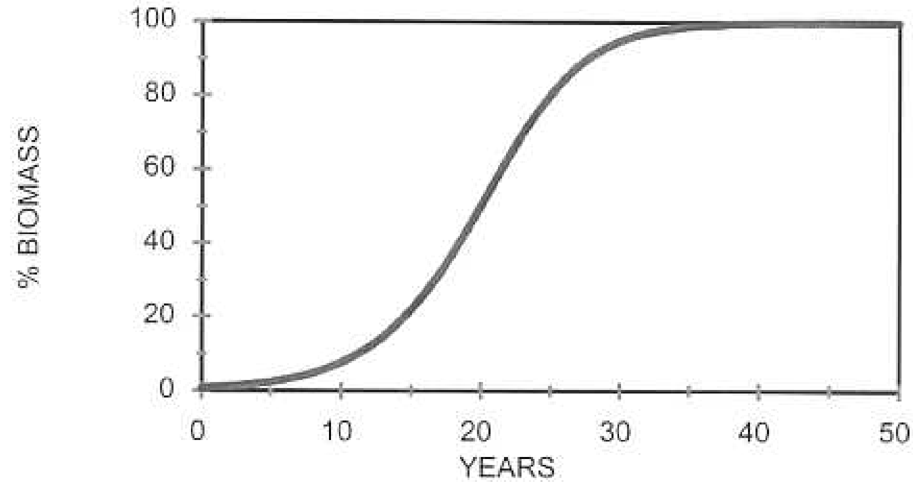


Figure 3. The logistic recovery model for an individual geoduck tract assuming a mean recovery time of 39 yrs for biomass to recover to its unfished level. The logistic parameters for the curve are $r = 0.2675$ and $K = 100$.

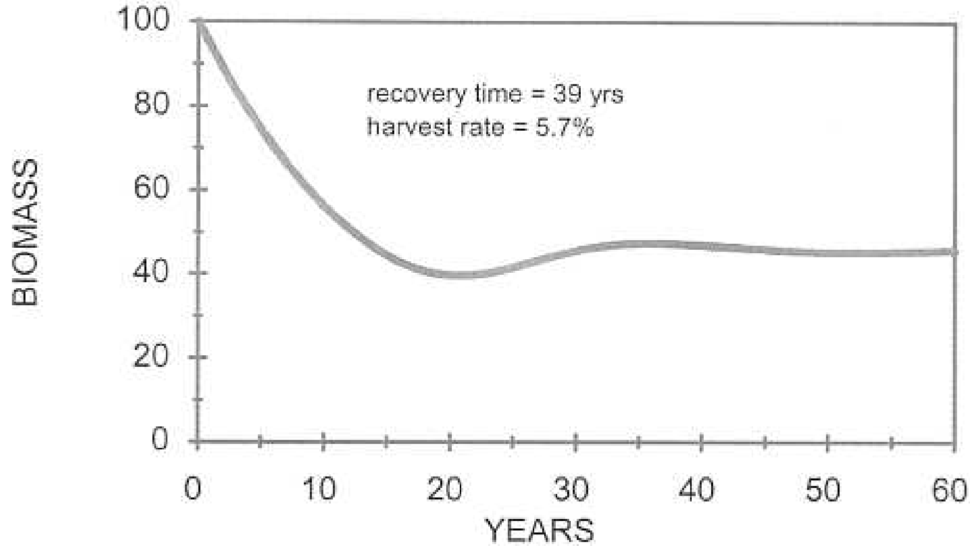


Figure 4. The effect of a constant harvest rate strategy ($\mu = 0.057$) on geoduck biomass, assuming an average recovery time to pre-fishing density on individual tracts of 39 yr. Predictions were calculated using the logistic recovery model described in the text.

Table 1 (continued). Geoduck survey data.

Tract name: Anderson Cove

Station	Geoduck Density (number/900 square feet) Prefishing May 21-22,1985	1st Postfishing October 3-4,1988	2nd Postfishing June 15,1992
1	38	1	12
2	14	4	0
10	16	5	17
17	112	5	20
18	88	3	8
19	48	4	10
25	57	3	7
26	50	1	13
27	26	1	29
28	37	7	18
29	18	9	17
35	76	5	12
36	35	3	6
Mean	47.31	3.92	13.00
n	13	13	13
s.d.	29.60	2.36	7.37
CV	0.63	0.60	0.57

Table 1 (continued). Geoduck survey data.

Tract name: Henderson

Station	Geoduck Density (number/900 square feet)		
	Prefishing May 1-29,1984	1st Postfishing July 21-22,1986	2nd Postfishing July 1-15,1992
12	100	33	21
13	149	27	29
14	143	74	84
16	87	111	177
17	185	80	58
18	56	115	38
19	141	56	44
20	190	59	56
21	159	24	61
22	230	32	72
23	118	13	65
24	39	10	43
31	121	60	70
32	110	44	81
33	143	33	94
34	199	82	59
35	282	91	108
36	318	32	9
64	182	68	122
65	151	57	63
68	131	21	81
69	47	5	99
102	117	6	46
103	73	107	50
104	166	90	26
105	242	11	79
106	286	73	179
107	339	158	85
108	211	120	169
114	314	80	29
115	189	54	45
117	195	121	69
118	63	21	24
Mean	165.94	59.64	70.76
n	33	33	33
s.d.	79.83	39.59	42.43
CV	0.48	0.66	0.60

Table 1 (continued). Geoduck survey data.

Tract name: Fern Cove

Station	Geoduck Density (number/900 square feet) Prefishing May 9-18,1983	1st Postfishing July 18-19,1985	2nd Postfishing June 18-25,1992
1	133	315	141
2	126	53	48
4	237	16	62
7	81	6	10
8	23	131	181
12	158	94	179
15	141	106	232
16	42	8	13
17	162	108	221
20	43	6	5
21	182	80	145
22	194	206	288
26	31	40	20
27	162	121	29
28	162	297	67
29	20	13	29
30	72	15	33
31	105	104	26
32	176	167	126
33	163	208	397
39	3	6	1
40	6	13	3
41	8	13	3
42	12	13	16
43	40	108	23
53	196	138	439
54	148	46	261
55	73	13	221
56	31	7	100
61	69	5	14
62	83	13	31
63	146	113	122
67	146	5	152
68	237	37	229
73	77	147	14
74	232	388	307
Mean	108.89	87.75	116.33
n	36	36	36
s.d.	72.05	97.08	119.39
CV	0.66	1.11	1.03

Table 1 (continued). Geoduck survey data.

Tract name: Walan Point

Station	Geoduck Density (number/900 square feet)		
	Prefishing June 3-4,1985	1st Postfishing Sept. 20,1988	2nd Postfishing Sept. 1,1993
1	93	8	31
2	48	4	6
7	44	10	16
8	80	5	24
9	94	7	14
10	70	13	13
11	91	12	3
12	29	7	6
13	35	11	10
14	37	9	14
32	27	7	11
33	28	2	6
34	17	4	6
35	17	7	10
36	32	5	13
37	26	2	9
38	17	3	11
39	49	1	13
40	42	0	27
41	66	1	12
42	47	2	4
43	31	12	3
44	45	14	4
45	22	7	7
Mean	45.29	6.38	11.38
n	24	24	24
s.d.	24.49	4.14	7.30
CV	0.54	0.65	0.64

Table 1 (continued). Geoduck survey data.

Tract name: Vashon East

Station	Geoduck Density (number/900 square feet) Prefishing *April 19,1983 **June 6,1979	1st Postfishing July 22-23,1985	2nd Postfishing Sept 14-16,1993
5*	277	36	84
7*	193	12	68
9*	226	20	58
11*	241	17	86
12*	199	9	94
13**	116	14	75
14*	158	6	44
15*	175	12	102
16*	183	8	32
17*	218	9	68
18*	114	3	23
19*	187	16	23
20*	125	7	14
21*	188	7	25
22*	82	27	31
23*	197	16	47
25*	110	14	54
26*	158	53	116
29*	112	24	87
30*	83	38	150
31*	108	32	55
33*	96	15	151
34**	77	41	24
36*	55	118	63
38*	179	55	87
39*	154	64	219
41**	51	77	202
44*	105	46	139
45*	111	44	228
Mean	147.52	28.97	84.45
n	29	29	29
s.d.	58.01	25.86	59.03
CV	0.39	0.89	0.70

Table 1 (continued). Geoduck survey data.

Tract name: Mahnckes

Station	Geoduck Density (number/900 square feet) Prefishing June 6,1983	1st Postfishing July 10,1985	2nd Postfishing May 3,1993
7	187	20	84
8	131	18	44
9	159	30	127
10	220	25	97
11	184	35	79
12	136	30	107
13	158	30	139
14	199	39	71
15	213	23	145
16	175	59	77
17	135	16	83
18	223	46	240
19	84	5	41
20	177	46	134
21	221	67	128
22	274	64	117
25	201	115	151
26	238	96	185
30	123	245	238
31	142	6	0
32	108	191	187
33	116	134	228
34	127	19	257
35	16	0	364
38	84	36	248
39	123	87	99
42	47	31	25
43	36	40	49
Mean	151.32	55.46	133.71
n	28	28	28
s.d.	63.06	56.60	84.02
CV	0.42	1.02	0.63

Table 1 (continued). Geoduck survey data.

Tract name: Dougall Point 1A

	Geoduck Density (number/900 square feet)		
Station	Prefishing April 3,1984	1st Postfishing July 10,1986	2nd Postfishing July 11-12,1994
1	74	57	61
2	90	17	46
3	125	13	34
4	158	16	43
5	19	4	28
6	238	3	19
7	277	3	38
8	40	21	23
10	165	8	20
11	40	17	20
12	175	4	12
13	120	7	19
14	47	14	15
15	91	10	24
Mean	118.50	13.86	28.71
n	14	14	14
s.d.	77.09	13.77	13.93
CV	0.65	0.99	0.49

Table 1 (continued). Geoduck survey data.

Tract name: Fudge Point

Station	Geoduck Density (number/900 square feet) Prefishing May 17-19,1982	1st Postfishing June 14,1984	2nd Postfishing July 12-22,1994
1	100	64	91
2	46	49	81
4	127	7	17
5	119	34	57
6	74	26	27
7	88	43	37
8	131	61	26
9	71	3	21
10	91	8	10
11	128	22	17
12	134	20	14
13	120	30	21
14	29	10	10
15	92	8	6
16	130	21	38
17	113	34	118
18	134	84	102
24	33	4	21
25	81	10	20
26	142	11	11
27	176	13	50
28	156	33	65
Mean	105.23	27.05	39.09
n	22	22	22
s.d.	38.61	21.85	32.80
CV	0.37	0.81	0.84

Table 2. Projected recovery time of fished geoduck tracts to pre-fishing density:

GEODUCK TRACT	MEAN GEODUCK DENSITY (no./900 square ft) prefishing	first postfishing	second postfishing	% decrease i density due to fishing	increase in postfishing density (no./900 sq ft	years of recovery	recruitment (no./sq ft/yr)	PROJECTED RECOVERY TIME (YRS) partial recovery	recovery after 100% catch
Indian Island/Kinney Point	94.36	14.18	61.45	84.97	47.27	5.68	0.009	9.63	11.34
Big Hunter	116.06	12.75	44.00	89.01	31.25	10.80	0.003	35.70	40.11
Kala Point	68.25	3.25	9.20	95.24	5.95	5.65	0.001	61.69	64.77
North Vashon	102.63	60.79	121.33	40.76	60.54	7.90	0.009	5.46	13.40 *
Treble Point	283.43	125.86	194.86	55.59	69.00	7.84	0.010	17.91	32.22 *
Agate Pass	79.76	28.71	73.29	64.00	44.57	10.98	0.005	12.57	19.64 **
Anderson Cove	47.31	3.92	13.00	91.71	9.08	3.70	0.003	17.69	19.29
Henderson	165.94	59.64	70.76	64.06	11.12	5.97	0.002	57.06	89.08 *
Fern Cove	108.89	87.75	116.33	19.41	28.58	6.93	0.005	5.13	26.42 *
Walan Point	45.29	6.38	11.38	85.92	5.00	4.95	0.001	38.53	44.84
Mahnckes	151.32	55.46	133.71	63.35	78.25	7.82	0.011	9.58	15.12
Vashon East	147.52	28.97	84.45	80.36	55.48	8.16	0.008	17.43	21.69
Fudge Point	105.23	27.05	39.09	74.30	12.05	10.10	0.001	65.53	88.20 *
Dougall Point 1A	116.50	13.86	28.71	88.31	14.86	8.01	0.002	56.40	63.87
Dougall Point 2	142.13	25.88	45.38	81.79	19.50	10.08	0.002	60.09	73.46
Minimum	45.29	3.25	9.20	19.41	5.00	3.70	0.001	5.13	11.34
Maximum	283.43	125.86	194.86	95.24	78.25	10.98	0.011	65.53	89.08
Mean	118.44	36.96	69.80	71.92	32.83	7.64	0.005	31.36	41.56
STD	58.24	34.91	52.81	21.09	24.62	2.20	0.004	23.13	27.51
CV (std/mean)	0.49	0.94	0.76	0.29	0.75	0.29	0.742	0.74	0.66
Restricting analysis to beds with significantly different means:									
Minimum									11.34
Maximum									73.46
Mean									39.39
STD									23.79
CV (std/mean)									0.60

* no statistically significant difference between mean first and mean second postfishing densities

** no statistically significant difference between mean pre-fishing and mean first postfishing densities

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Table 2. Projected recovery time of fished geoduck tracts to pre-fishing density:

GEODUCK TRACT	MEAN GEODUCK DENSITY (no./900 square ft)			% decrease i density due to fishing	increase in postfishing density (no./900 sq ft	years of recovery	recruitment (no./sq ft/yr)	PROJECTED RECOVERY TIME (YRS)	
	prefishing	first postfishing	second postfishing					partial recovery	recovery after 100% catch
Indian Island/Kinney Point	94.36	14.18	61.45	84.97	47.27	5.68	0.009	9.63	11.34
Big Hunter	116.06	12.75	44.00	89.01	31.25	10.80	0.003	35.70	40.11
Kala Point	68.25	3.25	9.20	95.24	5.95	5.65	0.001	61.69	64.77
North Vashon	102.63	60.79	121.33	40.76	60.54	7.90	0.009	5.46	13.40 *
Treble Point	283.43	125.86	194.86	55.59	69.00	7.84	0.010	17.91	32.22 *
Agate Pass	79.76	28.71	73.29	64.00	44.57	10.98	0.005	12.57	19.64 **
Anderson Cove	47.31	3.92	13.00	91.71	9.08	3.70	0.003	17.69	19.29
Henderson	165.94	59.64	70.76	64.06	11.12	5.97	0.002	57.06	89.08 *
Fern Cove	108.89	87.75	116.33	19.41	28.58	6.93	0.005	5.13	26.42 *
Walan Point	45.29	6.38	11.38	85.92	5.00	4.95	0.001	38.53	44.84
Mahnckes	151.32	55.46	133.71	63.35	78.25	7.82	0.011	9.58	15.12
Vashon East	147.52	28.97	84.45	80.36	55.48	8.16	0.008	17.43	21.69
Fudge Point	105.23	27.05	39.09	74.30	12.05	10.10	0.001	65.53	88.20 *
Dougall Point 1A	118.50	13.86	28.71	88.31	14.86	8.01	0.002	56.40	63.87
Dougall Point 2	142.13	25.88	45.38	81.79	19.50	10.08	0.002	60.09	73.46
Minimum	45.29	3.25	9.20	19.41	5.00	3.70	0.001	5.13	11.34
Maximum	283.43	125.86	194.86	95.24	78.25	10.98	0.011	65.53	89.08
Mean	118.44	36.96	69.80	71.92	32.83	7.64	0.005	31.36	41.56
STD	58.24	34.91	52.81	21.09	24.62	2.20	0.004	23.13	27.51
CV (std/mean)	0.49	0.94	0.76	0.29	0.75	0.29	0.742	0.74	0.66

Restricting analysis to beds with significantly different means:	
Minimum	11.34
Maximum	73.46
Mean	39.39
STD	23.79
CV (std/mean)	0.60

* no statistically significant difference between mean first and mean second postfishing densities

** no statistically significant difference between mean pre-fishing and mean first postfishing densities

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Table 3. Results of the student's t-test (with unequal variance) comparing mean densities on fish
Geoduck densities were log-transformed prior to performing the t-tests.

GEODUCK TRACT	PREFISHING MEAN DENSITY V 1ST POSTFISHING MEAN DENS			1ST POSTFISHING MEAN DENSI 2ND POSTFISHING MEAN DEN		
	reject null H	t-value	t critical (one-tail)	reject null H	t-value	t critical (one-tail)
Indian Island/Kinney Poi	yes	6.45	1.68	yes	-4.08	1.68
Big Hunter	yes	2.37	1.72	yes	-2.78	1.70
Kala Point	yes	10.93	1.69	yes	-2.43	1.70
North Vashon	yes	2.04	1.68	no	-1.45	1.68
Treble Point	yes	3.58	1.73	no	-1.31	1.71
Agate Pass	no	0.91	1.69	yes	-2.67	1.68
Anderson Cove	yes	9.79	1.71	yes	-3.47	1.72
Henderson	yes	6.60	1.67	no	-1.51	1.67
Fern Cove	yes	1.96	1.67	no	-0.75	1.67
Walan Point	yes	10.59	1.68	yes	-3.03	1.68
Mahnckes	yes	5.52	1.68	yes	-3.47	1.67
Vashon East	yes	10.66	1.68	yes	-5.58	1.67
Fudge Point	yes	7.53	1.69	no	-1.46	1.68
Dougall Point 1A	yes	7.46	1.71	yes	-3.76	1.72
Dougall Point 2	yes	4.30	1.78	yes	-1.93	1.80

yes = reject the null hypothesis that the two mean densities are equal.

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Table 4. Geoduck harvest at 15 fished tracts between the prefishing survey and first postfishing survey.

Tract name	Tract siz (acres)	Catch (number of geoducks rounded to nearest 1,000)
Indian Island/Kinney Point	76	361,000
Big Hunter	93	951,000
Kala Point	65	270,000
North Vashon	36	441,000
Treble Point	15	259,000
Agate Pass	156	3,625,000
Anderson Cove	65	96,000
Henderson	59	714,000
Fern Cove	116	472,000
Walan Point	152	353,000
Mahnckes	73	201,000
Vashon East	53	395,000
Fudge Point	70	574,000
Dougall Point 1A	26	351,000
Dougall Point 2	20	349,000

Stock Assessment of Subtidal Geoduck Clams (*Panopea abrupta*) in Washington

by

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January 2000

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Glossary

Annual mortality rate (A) - The number of animals which die during a year divided by the initial number.

Constant *F* strategy - A harvest strategy which sets the annual quota as a function of current population size and a recommended instantaneous fishing mortality rate.

CV - Coefficient of variation, a relative measure of statistical precision (the standard error of an estimator divided by the estimator, and expressed as a percentage).

DGPS - Differential Global Positioning System, a satellite navigational system which uses a shore-based slave station to provide extremely accurate position fixes on the surface of the earth.

DNR - Washington Department of Natural Resources.

Dig sample - A sample of geoducks (generally ten) dug with commercial water jet gear within a previously surveyed 900 ft^2 transect on a geoduck tract, used in estimating mean weight per geoduck.

Dimple - A visible depression or "show" caused by a geoduck or other clam siphon which is partially retracted in the substrate.

Equilibrium yield - The yield in weight taken from a stock when it is in equilibrium with fishing of a given intensity.

Exploitation rate (μ) - The fraction of the initial population removed fishing in one year; equivalent to the product of the annual mortality rate and the fishing mortality rate divided by the total mortality rate ($\mu = FA / Z$).

Fishing mortality rate (*F*) - The ratio of number of animals harvested per unit of time to the population abundance at that time, if all harvested animals were to be immediately replaced so that the population does not change (an instantaneous rate). The portion of total instantaneous mortality due to fishing.

Geoduck Atlas - An annual WDFW publication listing all known geoduck tracts in Washington, along with maps of their location, their commercial status, estimates of geoduck biomass, and other summary information.

Grid line - The primary sampling unit in geoduck surveys, along which a series of 900 ft^2 strip transects is aligned; usually run perpendicular to shore.

Harvestable geoducks - Geoducks of a size in which the siphon or "show" is likely to be seen by a diver; generally, geoducks with a total weight > 300 grams and >5 yrs old.

Harvest rate - Same as exploitation rate, see above.

Harvest strategy - A quantitative plan which states how catch will be adjusted from year to year, usually depending on the size of the stock.

MLLW(Mean Lower Low Water) - The arithmetic mean of the lower low water heights of a mixed tide observed over a specific 19-year Metonic cycle at a specific tidal reference station. Used to correct ambient depths (from diver depth gauges) to a standard tidal datum.

Natural mortality rate (*M*) - The ratio of number of animals which die from non-fishing causes per unit of time to the population abundance at that time, if all dead animals were to be immediately replaced so that the population does not change (an instantaneous rate). The portion of total instantaneous mortality due to natural (i.e., non-fishing) causes.

Rafeedie decision - The popular term for United States v. Washington No. 9213, subproceeding 89-3, a federal district court decision regarding treaty tribal rights to shellfish, including geoducks.

Show - When applied to geoducks, either a geoduck siphon visible above the substrate surface, or a depression or mark left in the substrate which can be identified as having been made by a geoduck.

Show factor - The ratio of geoduck shows visible during a single observation of any defined area to the true abundance of harvestable geoducks in that area.

Show plot - Permanently-marked subtidal areas in which the absolute number of harvestable geoducks is known from repeated tagging; show plots are used to estimate geoduck show factors.

SPR (Spawning Biomass Per Recruit) - The biomass of sexually mature members of a stock, expressed in terms of weight per recruit. Mathematically, the product of numbers-at-age, weight-at-age, and the proportion mature-at-age, summed over all ages in the population.

Stock-recruit (S-R) relationship - The functional relationship between the biomass (or number) of spawning stock and the resultant biomass (or number) of recruits.

Strip transect - See Transect below.

Subtidal geoduck - A geoduck living at a depth never uncovered by the tides (i.e., below the level of the extreme low spring tide at a given location).

TAC (Total Allowable Catch) - The number or weight of fish which may be harvested in a specific unit of time. As used in this report, the product of the estimated biomass of harvestable geoducks and the recommended annual harvest rate.

Total mortality rate (*Z*) - The ratio of number of animals which die from all causes per unit of time to the population abundance at that time, if all dead animals were to be immediately replaced so that the population does not change (an instantaneous rate).

Tract - A subtidal area with defined boundaries which contains geoducks. See *Definition of Key Terms* for a full discussion.

Transect - The secondary sampling unit for geoduck density. In this report, a standard strip transect 150 ft long by six ft wide (= 900 ft^2) within which divers count all geoducks which are "showing."

WDFW - Washington Department of Fish and Wildlife.

Abstract

WDFW is mandated to perform biological stock assessment of the commercial geoduck resource and to make annual recommendations on the Total Allowable Catch (TAC) for each geoduck management region. Systematically spaced strip transect surveys are used to estimate the density of harvestable geoducks within commercial tracts, and a sample of geoducks is taken from these transects to estimate average weight. Biomass estimates on commercial tracts are the product of mean biomass per unit area and the total area of the tract. Regional biomass estimates are the sum of all surveyed commercial tract estimates within the region. Regional TACs are the product of the regional biomass estimate and the recommended harvest rate. An age-based equilibrium yield model was used to predict the long-term consequences of various harvest rates, using geoduck life history parameters which were estimated from existing WDFW data and literature sources. The model predicts yield and spawning biomass per recruit over a range of fishing mortality rates. Five commonly-used constant harvest rate strategies were simulated with the model, including two based on yield-per-recruit analysis and three based on spawning biomass per recruit analysis. An $F_{40\%}$ strategy is recommended as a risk-averse policy for geoducks. Under an $F_{40\%}$ strategy, the recommended annual TAC is 2.7% of the current commercial biomass within a region.

Introduction

Geoduck clams (*Panopea abrupta*) dominate the biomass of benthic infaunal communities in many parts of Puget Sound. Goodwin and Pease (1989) summarized the biology and commercial dive fishery for geoducks, which began in 1970 in Washington state. Commercial fisheries also exist in British Columbia and Alaska (Campbell *et al.* 1998), and geoducks now provide the most valuable commercial clam harvest on the Pacific coast of North America. The average annual ex-vessel value of Washington's geoduck harvest from 1990-1998 was US$14 million. From 1971 through 1998, annual landings have averaged 3.3 million pounds.

The commercial geoduck fishery is jointly managed by two state agencies, Washington Department of Fish and Wildlife (WDFW) and the Department of Natural Resources (DNR), as well as the treaty Indian tribes with shellfishing rights affirmed by a 1994 federal district court judgement (the Rafeedie decision). WDFW's role is to perform biological stock assessment of the resource and to make recommendations on the Total Allowable Catch (TAC) which is expected to maintain a stable long-term commercial fishery.

WDFW began SCUBA diving surveys of geoducks in 1967, and surveys have continued on a yearly basis since that time, with a number of improvements and modifications. Treaty Tribes under co-management with the state began geoduck surveys in 1996. A modified Ricker yield-per-recruit model was adopted in 1981 for use in setting the statewide TAC. This inital research was updated and adopted by state and Tribal managers in 1997 with an equilibrium yield model.

This report describes the methods currently used by WDFW and treaty Tribes to assess subtidal geoduck populations and make annual recommendations on the TAC.

Part I of this paper describes the procedures used to estimate the biomass of harvestable geoducks on subtidal tracts of land. Part II describes the simulation of various harvest rate strategies via equilibrium yield modeling, and recommends a harvest rate based on this modeling to be used in the calculation of the TAC.

Goals and Objectives of Geoduck Stock Assessment

The long-term goal of geoduck stock assessment is to provide managers with the biological information needed to recommend a Total Allowable Catch (TAC). Currently, managers recommend separate TACs for each of six geoduck management regions, the boundaries of which are shown in Figure 1.

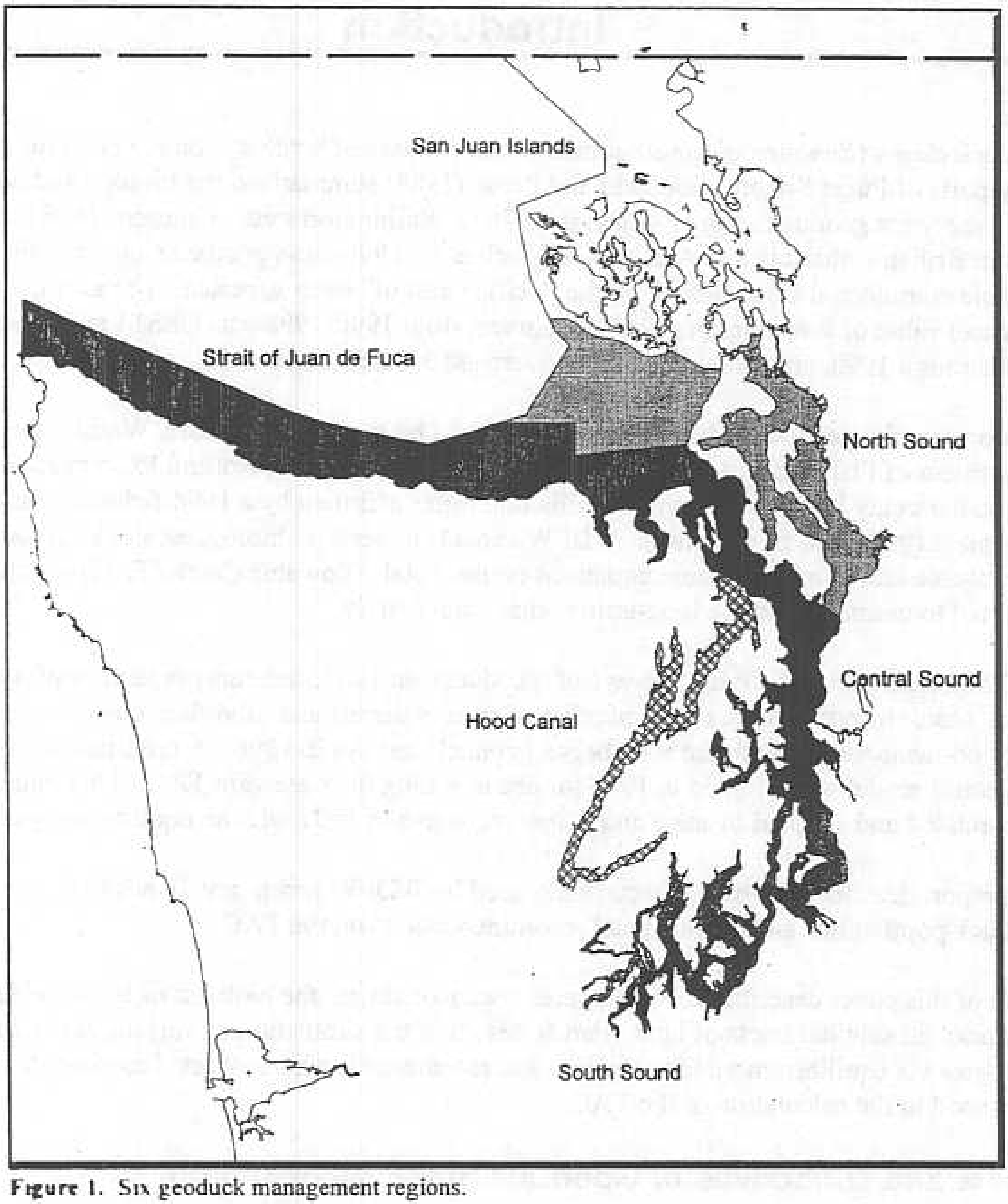


Figure 1. Six geoduck management regions.

The TAC for a given management region is the product of the current estimate of harvestable biomass of geoducks in the region and the recommended harvest rate for the region. Thus, the two short-term goals of geoduck stock assessment are: 1) To estimate harvestable geoduck biomass in each region, and: 2) To recommend a biologically sustainable harvest rate.

In order to reach the first of these short-term goals -- an estimation of harvestable biomass in each region -- dive surveys are carried out each year on relatively small subtidal areas known as "tracts." The objective of such surveys is to estimate the biomass of harvestable geoducks within the confines of the tract. The sum of biomass estimates on all commercial tracts surveyed within a region comprises the regional biomass estimate. Since only a few tracts can be surveyed each year, regional biomass estimates consist of the most recent estimate for each surveyed tract in the region, with known commercial catches subtracted from those tracts which are fished. Biomass estimates for all surveyed tracts are summarized yearly in the annual Geoduck Atlas. The Atlas is published by WDFW in collaboration with the treaty Tribes and is available from the Point Whitney Shellfish Laboratory. Part I of this paper describes the current procedures for making biomass estimates.

In order to reach the second short-term goal -- recommendation of an annual harvest rate -- estimates of important geoduck life history parameters were used to drive an age-based equilibrium yield model. The objective of this yield modeling was to predict the long-term effect of various harvest rates on equilibrium yield and spawning biomass per recruit, and to recommend one of these harvest rates for use in computing regional TACs. Part II of this paper describes the yield modeling and the rationale for recommending a particular harvest rate.

Figure 2 is a flow chart which shows these steps leading to regional TAC recommendations.

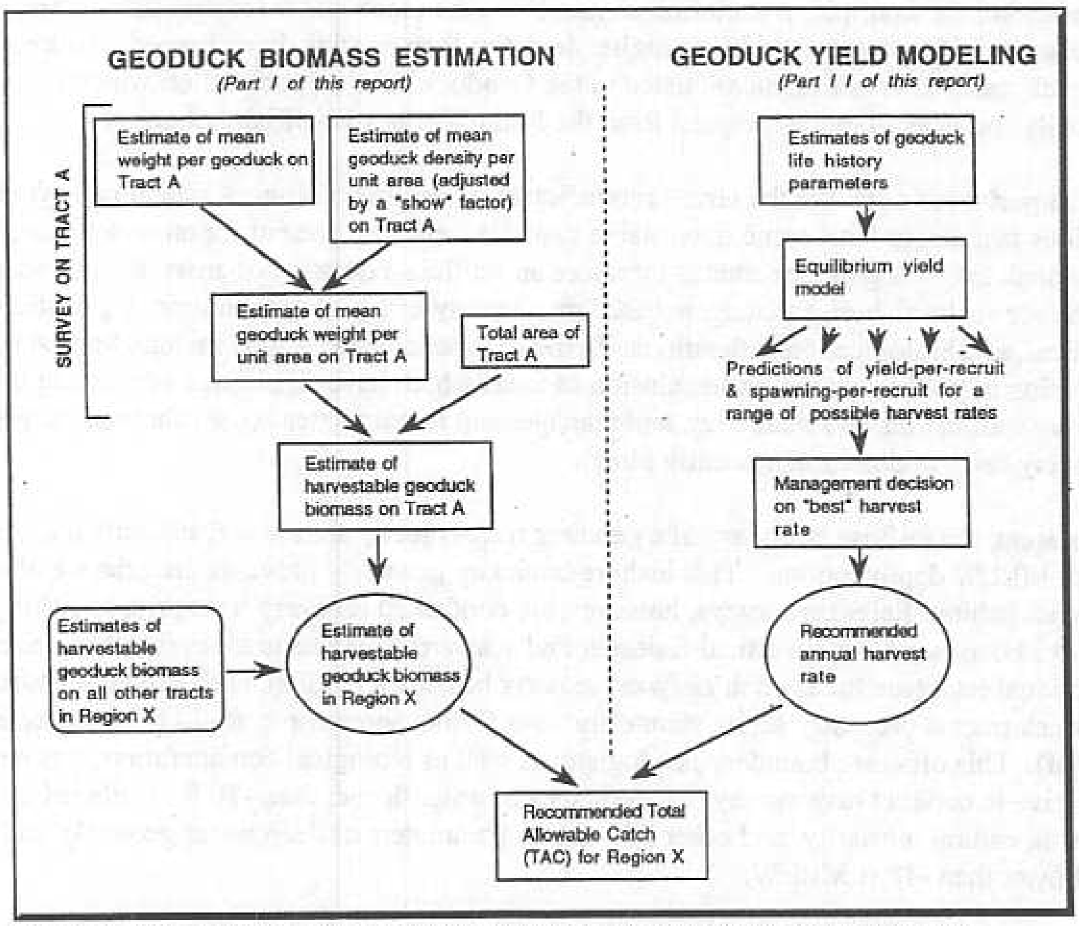


Figure 2. Steps leading to a geoduck biomass estimate on Tract "A" and an annual TAC recommendation for Management Region "X."

Definition of Key Terms

Three key terms -- geoduck tract, geoduck bed, and harvestable geoducks -- are used extensively throughout this paper. All three deserve a thorough definition because they are frequently a source of confusion for biologists, managers, and the public.

Geoduck Tract

A geoduck tract is any subtidal area with well-defined boundaries which contains geoducks. Boundary lines are typically referred to as inshore, offshore, and side boundaries. ***Commercial tracts*** are those tracts in which geoduck densities are considered high enough to support a fishery and which have no other drawbacks to fishing (e.g., pollution, narrow width, land-use conflicts, poor quality geoducks, difficult digging conditions, conflicts with threatened or endangered species or their habitats, etc.). ***Non-commercial tracts*** are those tracts which cannot be fished for one or more reasons, including those listed above. The status of a tract is always subject to change; for example, commercial tracts may become non-commercial if they become polluted, or if they are fished out following a commercial harvest; non-commercial tracts may become commercial, for example, if pollution abates, if the area recovers from past fishing, market prices increase, or if new surveys indicate higher densities than previously estimated. All known geoduck tracts in Washington are listed in the Geoduck Atlas, a publication which is updated annually and is available on request from the Point Whitney Shellfish Laboratory.

It is important to note that the term "geoduck tract" has little biological meaning, beyond the obvious fact that at least some harvestable geoducks must be present for an area to be considered a geoduck tract. A geoduck tract is therefore an artificial construct of areas, the boundaries of which are set by fisheries managers based on a variety of logistic, economic, legal, social, political, and biological considerations. Some of these considerations include harvest control, exclusion of polluted areas, and exclusion of areas which have significant conflicting uses such as ferry traffic, marine sanctuaries, and management research areas (e.g., show plots, geoduck recovery beds, and natural mortality plots).

At present, the inshore boundary of a geoduck tract is set by statute and state/tribal agreements at -18 ft MLLW depth contour. This inshore boundary generally prevents disturbance of sensitive eelgrass habitat. Eelgrass surveys, however, are conducted on every tract prior to fishing, and the inshore boundary is set 2 vertical ft deeper and seaward where eelgrass is found to occur on an individual tract (see the section *Eelgrass surveys* below for details). The offshore boundary of a geoduck tract is presently set by statute and state/Tribal agreements at -70 ft (uncorrected for tide height). This offshore boundary is a logistic as well as biological consideration; it is not cost-effective to conduct dive surveys of geoducks in water deeper than -70 ft. Little is known about growth, natural mortality, and other life-history parameters of deep water geoducks and geoducks shallower than -18 ft MLLW.

Although the inshore and offshore boundaries of what is currently considered a geoduck tract are strictly defined by statute and state/tribal agreements as noted above, the side boundaries of a tract are flexible. Side boundaries should enclose areas which have adequate survey information, and therefore may never lie more than 500 feet from the nearest grid line of transects (see *Variations on the standard grid line layout* below). Subtidal geoducks may be found along the entire shoreline of Puget Sound, albeit at very low densities in some areas. Thus, there is no specific point along the shoreline at which any tract can be said to "end" because geoducks are no longer present. In some cases, managers fix the "end" of a tract at the point along the shore where geoduck density falls below the current standard for commercial density. This is an arbitrary economic standard, however, which is subject to change with market prices. Virtually all commercial geoduck tracts contain areas within which density falls below the commercial level.

Besides the density of geoducks, other considerations in setting the side boundaries of tracts include: navigational channels, ferry lanes, steeply sloping bottom contours which "pinch" the tract to a width which makes commercial fishing impractical, and prohibited areas classified as such by the Washington Department of Health. Some tracts in the current Geoduck Atlas end simply at the point where biologists ran out of time during the survey season to continue surveys along the shoreline.

The side boundaries of a tract may be set before performing surveys, during the survey, or afterwards. In any case, the final side boundaries of a surveyed tract are usually modified based on survey findings. For example, survey transects may fall within areas which are later found to be polluted or near navigational hazards, and these transect data may later be eliminated from the tract. It is usually easier and more cost-effective to throw out survey data from small portions of a tract than to return to the field and perform additional surveys.

Because tract boundaries are set at the convenience of fisheries managers, there is, in theory at least, no limit on the size of a geoduck tract. There are, however, practical limits. The management and survey costs per acre increase dramatically as tracts become smaller, making very small tracts uneconomical to lease. The smallest tract listed in the 2000 Geoduck Atlas is four acres, and the smallest tract ever commercially fished was five acres (Cooper Point). Extremely large tracts generally contain so much geoduck biomass that they may be divided into smaller tracts which can be fished in accordance with annual TACs or harvest shares. Large tracts also present compliance and enforcement problems. For example, the largest tract listed in the 1997 Geoduck Atlas was 2,452 acres (Jamestown 1, Tract #00450). Based on recent surveys this tract was subsequently reconfigured, and in the 2000 Geoduck Atlas appears as a 331 acre tract. The largest commercial tract in the 2000 Geoduck Atlas is 723 acres (Battle Point North, Tract #07000). The mean size of all tracts listed in the 2000 Geoduck Atlas is 106 acres (n = 267 tracts).

Existing tract boundaries may change annually to fit management needs. Large tracts are frequently divided into smaller ones, and small adjacent tracts are often joined to form a single, larger tract. New surveys may increase the side boundaries of certain tracts which had been previously surveyed.

Geoduck Bed

A geoduck bed is an aggregation of geoduck clams in the marine environment. Geoducks will recruit to areas with suitable substrate (sand or sand/mud mixtures), adequate current, sufficient food, and few predators. Geoduck beds occur from the intertidal zone to deep subtidal areas. A geoduck tract is typically a subset of a geoduck bed.

Harvestable Geoducks

Harvestable geoducks are those of a size in which the siphon or "show" is likely to be seen by a diver. Virtually all geoducks visible to experienced divers are of a marketable size. Washington samples indicate that geoducks first enter the fishery at 300 g, a weight which is usually attained between five and seven years (see the sections on *Growth* and *Fishery selectivity* in Part II of this paper). WDFW geoduck transect counts and weight samples made using the procedures described in this paper are assumed to closely mimic this commercial pattern of selectivity. In support of this assumption, we note that only 2% of the 11,181 geoducks sampled by WDFW divers during surveys from 1973-1985 weighed less than 300 g (Goodwin and Pease 1987).

Obviously, geoducks which are too small to be seen by divers are neither harvested by fishers nor counted by WDFW surveyers. Therefore, the procedures described in this paper for estimating the biomass of *harvestable* geoducks necessarily underestimate *total* geoduck biomass, because most geoducks <300 grams or <4 yr old are not counted. The only method which has been used to effectively sample geoducks smaller than this size in a quantitative way is excavation with a venturi suction dredge (Goodwin and Shaul 1984). Venturi samples, while useful for recruitment research on a very small spatial scale, are far too laborious and costly for estimating geoduck densities over large areas.

Part I. Estimation of Harvestable Geoduck Biomass

Sample Design for Estimating Geoduck Biomass

The objective of geoduck surveys is to estimate the biomass of harvestable geoducks within a specific tract. Biomass per unit area within the tract is estimated as the product of mean density and mean weight per geoduck; total biomass on the tract is estimated as the product of biomass per unit area and total area. Strip transect surveys are first carried out to estimate mean density within the tract, and a sample of geoducks is later taken from a subsample of these transects to estimate mean weight per geoduck.

The sample or target population is therefore all harvestable geoducks within the tract boundary. The experimental or sampling unit for geoduck density is a 900 ft^2 strip transect. The estimator is the mean density (in numbers per ft^2) of harvestable geoducks, i.e., the mean density from all transects taken within the tract. The experimental or sampling unit for geoduck weight is a cluster sample of ten geoducks haphazardly dug with commercial gear from a transect. The estimator is the mean weight (in grams) of all geoducks sampled within the tract.

The subsections below present the sampling and statistical methods used to estimate mean density, mean weight per geoduck, total biomass, and the statistical precision of the total biomass estimate

Estimation of Mean Geoduck Density

The density of harvestable geoducks within a tract is estimated by a systematic sampling technique first developed in 1967 (Goodwin 1973; Goodwin and Pease 1991). A series of standard strip transects, each comprising an area six ft wide by 150 ft long (a total area of 900 ft^2) are taken along grid lines which run directly offshore from the -18 ft MLLW contour to the -70 ft contour (uncorrected). The grid lines (primary sampling units) begin at a randomly-selected starting point along the shoreline of the tract and are spaced systematically in both directions thereafter at 1,000 ft intervals. Transects (secondary sampling units) are then taken back-to-back along each grid line. Figure 3 shows the arrangement of systematic samples on a typical tract. The section *Geoduck Survey Methods* below describes in detail the procedures used in the field.

The density of geoducks observed by divers within an individual transect is always an underestimate of the actual density present within that transect (Goodwin 1973; Goodwin 1977). Geoduck siphons may be retracted below the surface of the substrate, cryptic at the surface of the substrate, or obscured from view of the diver. The number of geoducks "showing" (i.e., observable to divers) compared to the number of geoducks actually present in the substrate is a function of various environmental factors such as food availability, water temperature, substrate type, algae cover, turbidity, and currents (Goodwin 1977).

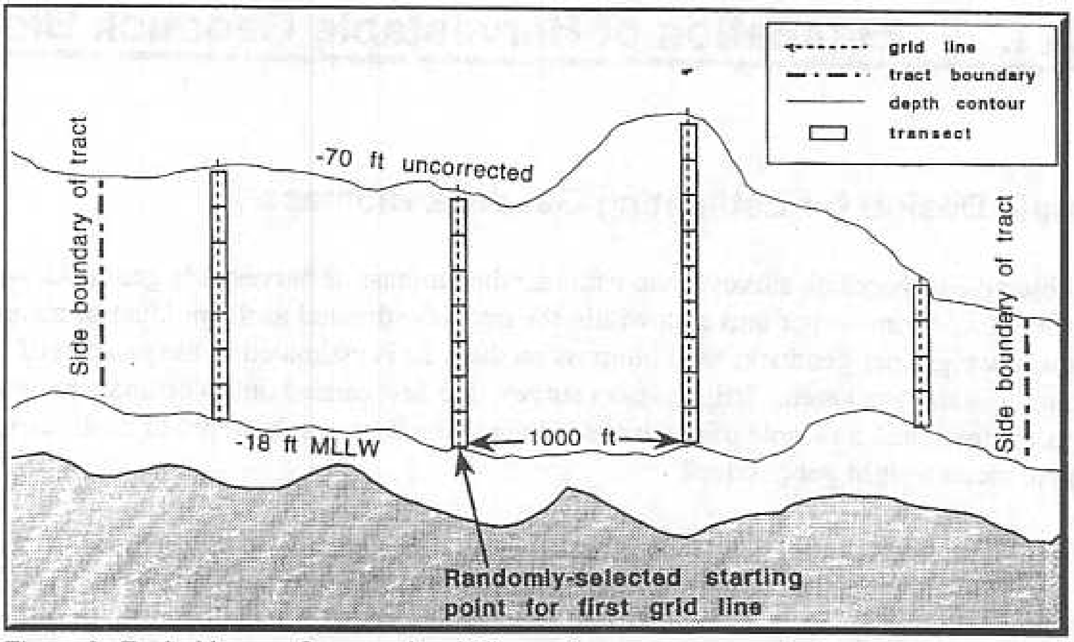


Figure 3. Typical layout of systematic grid lines and transects on a geoduck tract.

The estimate of geoduck density (number of geoducks per ft^2) for an individual transect is calculated by adjusting the observed density by a show factor as follows:

$$d_i = d_{obs}/S \quad (1)$$

where

d_i = density of geoducks (number per ft^2) on the *i*th transect

d_{obs} = density of geoducks (number per ft^2) observed by divers during a survey on the *i*th transect (for a 900 ft^2 transect, this is simply the total number of geoducks observed by both divers divided by 900). Note that the counts of both divers are summed to produce a single d_{obs} for each transect. Although it is tempting to consider each diver's count as a separate d_{obs} (therefore doubling the sample size), this would amount to "pseudoreplication" (Hurlbert 1984), because the two counts along the same 150-ft transect are obviously not independent.

S = "show factor" (within any defined area, the ratio of visible geoduck "shows" from a single observation and the true abundance of harvestable geoducks). A show factor of 0.75 is currently used to estimate density on all tracts for pre-fishing surveys unless there is a show plot established for a tract that will give site-specific data. Use of 0.75 as a constant show factor is a management decision that is assumed to give a conservative estimate of harvestable biomass. The section *Show plot surveys and show factors* below provides the basis for the 0.75 show factor, as well as detailed field procedures for establishing and counting a show plot.

The mean density of geoducks on a given tract is estimated as:

$$D = \Sigma d_i / n_D \tag{2}$$

where

D = estimated mean density of geoducks

d_i = density of geoducks (number per ft^2) on the *i*th transect, adjusted by show factor as described above

n_D = sample n for density (number of transects surveyed)

The variance of the mean density (δ^2_D) is estimated as

$$\delta^2_D = \Sigma(d_i - D)^2/n_D - 1 \tag{3}$$

Estimation of Mean Weight per Geoduck

Following transect surveys, a series of cluster samples, each consisting of ten geoducks, are taken with commercial water jet harvest gear at systematically spaced intervals along each of the survey grid lines. Empirical studies suggest that reasonably precise and unbiased weight samples can usually be obtained by taking a cluster sample of ten geoducks systematically at one of every six to eight transects, beginning from a randomly selected transect (see the section *Sample size* below). This procedure ensures that all water depths are sampled, an important consideration because depth is a known biological gradient with respect to geoduck weight (Goodwin and Pease 1991). Because of the considerable set-up time involved in digging samples, cluster samples from a few systematically spaced transects are far more cost-effective than samples of individual geoducks from a large number of systematically or randomly chosen transects. The section *Geoduck dig (weight) samples* below provides detailed field and laboratory procedures for selecting dig stations, digging and processing the samples.

Mean weight per geoduck on a given tract is estimated as:

$$W = \Sigma w_i / n_W \tag{4}$$

where

W = estimated mean weight per geoduck

w_i = weight of the *i*th geoduck from dig samples

n_W = sample n for weight

The variance of the mean weight per geoduck (δ^2_W) is estimated as:

$$\delta^2_W = \Sigma(w_i - W)^2/n_W - 1 \qquad (5)$$

Estimation of Total Geoduck Biomass on the Tract

The estimate of total geoduck biomass on a tract is calculated as:

$$B_{tract} = (D)(W)(A) \qquad (6)$$

where

B_{tract} = total geoduck biomass on a tract (in pounds)

D = estimated mean density of geoducks (number per ft^2, adjusted by a show factor as described above)

W = estimated mean weight per geoduck (in pounds)

A = total surface area of the tract (in ft^2) determined from GIS mapping software and tract maps prepared by DNR (see *Tract Mapping and Grid Line Placement Methods* below).

Precision of Geoduck Biomass Estimates

Statistical precision of the biomass estimate is reported in terms of the commonly-accepted 95% upper and lower confidence limits (i.e., $\alpha = 0.05$, two-tailed).

Confidence limits are calculated based on an estimate of the variance of the biomass (B), which is in turn the product of mean density and mean weight per geoduck. A standard variance-of-products formula (Goodman 1960) is used to calculate an unbiased estimate of this product. If geoduck density and weight per geoduck (i.e., D and W) are independently subject to sampling error (i.e., there is no correlation between density and weight), then the variance of B is given by:

$$\delta^2_B = D^2[\delta^2_W/n_W] + W^2[\delta^2_D/n_D] - [\delta^2_D\,\delta^2_W/n_D\,n_W] \qquad (7)$$

where

δ^2_B = variance of B, estimated geoduck biomass per ft^2

D = mean density of geoducks (number per ft^2 adjusted by a show factor as described above)

W = mean weight (pounds per geoduck)

δ^2_D = variance of mean density

δ^2_W = variance of mean weight

n_D = sample n for mean density (number of transects)

n_W = sample n for mean weight (number of geoducks weighed)

The standard error (se) of B is calculated as the square root of δ^2_B.

The 95% confidence bound for a given geoduck tract of known size is given by:

$$B_{tract} \pm (t_{0.05,2,v})(se)(A) \quad (8)$$

where

B_{tract} = estimated geoduck biomass on an entire tract (in pounds)

$t_{0.05,2,v}$ = tabled t-value, $\alpha = 0.05$, two-tailed, v = df (degrees of freedom)

se = standard error of B

A = total area of tract (in ft^2)

For pre-harvest surveys on commercial beds, state and Tribal managers have agreed on a required precision for total biomass estimates of ±30% at the $\alpha = 0.05$ confidence level. In other words, the 95% confidence limit as calculated above must lie within ± 30% of the estimate of B.

Sample Size

The goal of pre-fishing surveys on an individual tract is to survey a sufficient number of transects and dig a sufficient number of geoducks to allow an unbiased estimate of geoduck biomass with 95% statistical confidence bounds which lie within ± 30% of the biomass estimate itself (see the section above). On the majority of tracts, the sample size required to meet these goals can be achieved by running a series of transects along grid lines placed systematically every 1,000 feet along the -18 ft MLLW contour, and digging a cluster sample of ten geoducks at every sixth to eighth transect. However, it is not always possible to achieve the required precision with this sampling scheme, particularly on narrow tracts, small tracts, or tracts with highly variable substrates. Two methods are used to roughly estimate the sample size (i.e., the number of transects) needed to meet the statistical precision requirements:

1. Prior to performing the survey, an empirically derived "rule of thumb" may be used in conjunction with the known surface area of the tract to roughly estimate the required number of transects. Evidence from past surveys on a variety of beds indicates that the sampling intensity listed in Table 1 usually meets or exceeds the required degree of statistical

precision. Note, however, that these are rough guidelines for pre-survey planning only, and in no way guarantee that biomass estimates will meet the precision requirements.

Table 1. Empirically derived guidelines for roughly estimating the sample size (number of transects) needed to meet statistical precision requirements on geoduck tracts of different sizes.

Size of tract (acres)	Number of 900 ft^2 transects per acre
1-5	3
6-15	2
16-50	1
51-100	0.66
100+	0.33

2. Once transect surveys have been completed along grid lines spaced every 1,000 feet along the -18 ft MLLW contour, it is possible to determine whether additional transects must be run based on the variance of transect counts already performed. Table 2 shows the coefficients of variation (CVs) for both mean geoduck density (*D*) and mean weight per geoduck *(W)* from 13 recently-surveyed tracts, and suggests that precision of the biomass estimate is almost totally dependent on the variance of density. Doubling the CV of density almost always produces a result within one or two percentage points of the precision of the biomass estimate. For example, doubling the CV of density on the Eld Inlet East tract results in 28.2%; after geoduck samples were dug and weighed, confidence bounds on the estimate of biomass were ± 29.1% of the estimate. By contrast, Table 2 shows that there is no such relationship between the CV of weight and the precision of biomass estimates. Thus, from the standpoint of statistical precision of the biomass estimate, the number of geoducks sampled for *weight* and the *variance of the mean weight* are irrelevant based on the tracts listed in Table 1.

The relationship shown in Table 2 between the CV of mean density and the 95% confidence interval makes it possible to predict with near certainty the precision of a tract's biomass estimate while still in the field, long before any geoducks are dug for weight samples.

A hand-held calculator with statistical function capabilities can be used to readily estimate the CV of density in the field, after transect surveys have begun. Actual geoduck counts from each completed transect may be used for this calculation, without applying either a show factor or converting the counts to a density estimate; CVs are unit-free relative measures of variance, and will therefore be identical in any case. The procedure is as follows:

1. Individually enter the geoduck counts from all transects (d_{obs}).

2. Have the calculator estimate the mean number of geoducks per transect and the sample variance (*Ex*: mean = 56.91 geoducks/transect and sample variance = 1,782.36).

Table 2. Sample size at 13 commercial tracts, coefficients of variation (CVs) for mean geoduck density and mean weight per geoduck, and the resulting 95% confidence intervals on the biomass estimates. Calculations are based on initial tract estimates.

Tract	Size (acres)	n (number of transects)	Transects / acre	Dig samples	Transects / dig sample	CV of mean density (%)	CV of mean weight (%)	95% CI on biomass (as % of *B*)
Arcadia 2	26	27	1.04	6	4.5	9.6	4.5	20.8
Bridge	35	34	0.97	4	8.5	14.5	6.9	31.5
Eld Inlet East	54	31	0.57	5	6.2	14.1	4.6	29.1
Arcadia 3	55	43	0.78	7	6.1	12.2	4.8	25.7
Eld Inlet West	79	47	0.59	14	3.4	14.1	2.7	28.1
Arcadia 4	118	82	0.69	14	5.9	7.8	4.3	17.5
Skiff Point	126	41	0.33	11	3.7	8.6	3.9	18.5
Blake Is North	144	61	0.42	6	10.2	12.7	6.5	28.0
Port Gamble	217	161	0.74	45	3.6	7.7	1.8	15.6
Murden Cove	222	68	0.31	19	3.6	7.2	3.1	15.4
Olele Point	225	91	0.40	16	5.7	6.8	2.9	14.5
Jamestown	255	67	0.26	9	7.4	8.6	3.3	18.0
Warrenville	316	102	0.32	8	12.8	13.4	5.2	28.2

3. Divide the sample variance by the number of transects to produce the variance of the estimator (*Ex*: n = 117 transects, so 1,782.36/117 = 15.23).

4. Take the square root of this number to produce the standard error of the estimator (*Ex*: square root of 15.23 = 3.90).

5. Divide the standard error of the estimator by the mean number of geoducks per transect and multiply by 100 to produce the coefficient of variation (*Ex*: CV = (3.90/56.91)100 = 6.85).

6. Double the CV to roughly estimate the width of the 95% confidence bound as a percentage of the biomass estimate (*Ex*: 2(6.85) = ± 13.7%. In this example, the precision lies well below the required limits of ± 30%, so that additional transects need not be taken). Doubling the CV roughly approximates the tabled t-value of 1.96 for an infinite number of samples (given a two-sided test with $\alpha = 0.05$), and is usually sufficient for *rough* field calculations.

If using this method to determine when enough transects have been run, it is important to note that this estimate of sample size may only be carried out *after* transects have been taken in a representative fashion throughout the entire tract (e.g., along grid lines spaced systematically every 1,000 feet apart). It is entirely possible, for example, to reach the desired statistical precision after only a few transects have been taken in a tiny corner of the tract; such a sample would be precise, but would very likely be biased. The same is true for geoduck weight samples which, to avoid bias, should be taken at systematic, random, or stratified random intervals throughout the entire tract.

Additional transects may be needed for certain tracts to reach the desired level of precision. Placement of additional transects within a tract is discussed below in the section *Variations on the standard grid line layout*.

Rationale for Systematic Sampling

A systematic grid sample was chosen to estimate geoduck biomass rather than a simple random sample for reasons of cost and convenience. To avoid decompression sickness, divers are limited in the amount of time they may spend sampling at depth, so that economizing bottom time becomes a paramount consideration in choosing underwater sampling designs. Systematic samples provide far greater information per unit time than simple random sampling, as illustrated in the example below.

Each transect typically takes experienced divers four minutes to complete, plus the time required to descend and ascend from the dive. Divers generally take about one minute to descend, become oriented, and record initial data. When surfacing following the dive, divers must ascend at a rate between 0.5 and 1.0 ft per second. Additionally, WDFW divers are required by safety regulations to perform a three-minute safety stop at -10 to -15 ft on every ascent to decrease the risk of decompression sickness (WDFW Diving Operations Manual, November 1991). Thus, a single transect at -60 ft would take between 9 and 10 minutes, and a random sample of 50 such transects would require as much as 500 minutes of diver time; only 200 minutes of this time is actually spent surveying geoducks, while the remaining time is used for descents, ascents, and safety stops.

A systematic grid sample, on the other hand, is considerably more economical in terms of diver time because there is only one descent and one ascent per grid line. Thus, the same 50 transects taken along systematically-spaced grid lines (assume, for this example, ten grid lines and five transects per line) would require only 260 minutes of diver time, and only 60 minutes of this time is used in descents, ascents, and safety stops. In practice, the time savings of systematic sampling versus random sampling are even greater, because the US Navy Dive Tables require that bottom times be rounded up to the nearest five minute increment, thus imposing an additional "penalty" for numerous single-transect dives. The time savings of systematic samples over random samples increases on tracts which are extremely wide (i.e., where each line consists of many transects) and decreases on tracts which are narrow due to steeply sloping bottom contours. Extremely narrow tracts, however, may be economically sampled using systematically-spaced oblique or zig-zag lines (see *Variations on the standard grid line layout* below).

Besides the considerable savings in dive time, there are additional advantages to a systematic sample when surveying geoducks. Choosing a single random starting point along the shoreline and then spacing lines of transects every 1,000 feet is much simpler, with fewer start positions, and less prone to selection error than attempting to choose random 900 ft^2 samples throughout a tract. Systematic line sampling also permits the most precise mapping of boundaries and spatial patterns in geoduck density.

Despite the cost benefits of a systematic sample for geoducks, classic sampling theory cautions that there are two potential disadvantages to systematic sampling: 1) It is impossible to guarantee that the estimate of mean density derived from a systematic sample is unbiased, and; 2) It is not possible to obtain an unbiased estimator of the variance of mean density from a systematic sample.

While there is no guarantee, from a theoretical standpoint, that systematic samples of geoduck density will be unbiased, we believe that the sampling protocol outlined above is no more likely to produce biased estimates than a simple random sample of the same size. This is because there are no known biological gradients affecting geoduck distribution which occur systematically along the shoreline. Put another way, we know of no variations in geoduck density which occur periodically at 1,000-foot intervals along the shoreline. (Gradients in geoduck density do exist along shorelines, and some of these gradients are even predictable -- such as generally decreasing numbers of geoducks from the mouth of a bay to the stagnant head of the bay. But note that this is not a *systematic* gradient, and could be sampled in a representative way by both systematic or simple random schemes).

On the other hand, lines placed systematically along depth contours (or running parallel to the shoreline) invite biased results, because depth is a known biological gradient with respect to geoduck density (Goodwin and Pease 1991). This is particularly true of samples consisting of transects along only one or two such lines. Under the recommended sampling protocol above, each line of transects running from the shallow boundary of a tract to its deep water boundary cuts completely *across* the depth gradient, minimizing depth-related bias.

The second potential problem associated with systematic samples is that they do not produce an unbiased estimate of variance (in our case, variance surrounding the estimate of mean geoduck density). The sample design protocol used here calculates variance using the simple random sample formula. Thompson (1992) notes that this leads to unbiased variance estimates only if the population units are randomly distributed; in most natural populations, this procedure tends to overestimate the variance of the mean. Thus, estimates of variance surrounding mean geoduck density when using this sample design are likely to be higher than the true variance. This in turn will tend to inflate the variance estimate surrounding total biomass, and widen the 95% confidence bounds on biomass.

We believe that these are, on balance, minor concerns, and concur with Hilborn and Walters (1992) who recommend systematic samples over simple random samples for surveys of abundance.

Tract Mapping and Grid Line Placement Methods

Individual geoduck tracts are mapped prior to performing surveys. Precise mapping is required for the following reasons:

1. To provide an accurate estimate of the tract's total surface area, which is used in Equation 6 above to estimate harvestable geoduck biomass on the tract.

2. To provide surveyers with information on depth contours which may influence the alignment of the systematic grid lines (see *Variations on the standard grid line layout* below).

3. To provide surveyers with an estimate of the sample size (i.e., the number of transects) needed to meet the required level of statistical precision.

4. To provide surveyers and managers with an estimate of the labor and time costs required to survey the tract.

5. To provide a precise post-survey spatial mapping of both transect locations and geoduck densities within the tract.

6. To develop reproducible and verifiable survey results.

Tract mapping has evolved considerably since geoduck surveys began in Washington in the late 1960s. During these early years, survey locations were first estimated by eye and later came to rely on navigational fixes from LORAN equipment. In recent years, the availability of sophisticated electronic field equipment such as Differential Global Positioning Systems (DGPS) and laser range finders, as well as computerized Geographic Information Systems (GIS), has made it possible to plot survey locations and estimate the surface area of tracts far more precisely than in the past. The sections below describe the methods currently used to map tracts and lay out the sampling grid lines prior to a survey.

Tract Mapping and Surface Area Estimates

Tracts to be surveyed by WDFW are initially mapped by DNR at a scale of one inch = 1,000 ft using a survey-grade DGPS unit. For most current surveys, DGPS positions are justified and plotted on either the NAD 27 (North American Datum 1927) or the WGS 84 (World Geodetic Survey 1984) geographic survey datum. These maps show the shoreline, the inshore, offshore and side boundaries of the tract, and fixed aids to navigation which may be useful in laying out the systematic grid lines for the survey. Side boundaries for the initial tract map depend on information from previous surveys and other management considerations, and are likely to change once survey data are analyzed.

In the case of tracts which have never been surveyed before, exploratory dives are often made to determine the extent of commercial geoduck densities. These exploratory dives may involve underwater sledding, single "bounce" dives spaced haphazardly throughout the area, swims along the shoreline paralleling a depth contour, or haphazardly-placed transect surveys. Such exploratory dives, while useful in defining the geographic boundaries of a tract, do not constitute valid geoduck surveys and cannot be used to estimate either density or biomass for the following reasons: 1) The samples are not systematically or randomly placed, increasing the risk of bias; 2)

Sample size is usually too small to provide the required degree of statistical precision; 3) Variants on the transect method such as sledding or bounce dives cannot be reliably adjusted for either the area surveyed or by existing show factor data; and 4) Depth contour swims are likely to provide biased estimates of geoduck density because they parallel depth, a known biological gradient of geoduck density (Goodwin and Pease 1991).

Once the initial boundaries of a tract have been determined and mapped, estimates of a tract's surface area are estimated with a scaled overlay sheet. Overlay sheets available from the Washington Department of Natural Resources (DNR) Inventory Section are scaled to one inch = 1,000 ft, requiring that the map be scaled appropriately prior to estimating acreage. The overlay sheet is placed haphazardly over the map, and the number of dots on the overlay sheet lying within the tract boundaries is counted, each dot representing one acre. This procedure is repeated several times and the average is taken as the best estimate of surface area.

Tract area estimates are also made by digitizing tract boundary data in MapInfo, a computerized geographic information system capable of calculating surface area. For most current surveys, DGPS fixes based on either the NAD 27 (North American Datum 1927) or the WGS 84 (World Geodetic Survey 1984) datum are used as input. It is absolutely essential that the same datum be used in creating maps and fixing positions in the field, or huge discrepancies in positions and area estimates will result. These computer-generated estimates of tract area are used to verify the estimate produced by the dot-overlay method.

The surface areas of tracts based on the initial mapping almost invariably change following the survey and prior to finalizing the biomass estimates on a tract. Side boundaries, for example, are likely to shrink if surveys or subsequent information indicate that low geoduck densities, polluted areas, difficult digging conditions, or narrow "pinched" depth contours merit a smaller tract. Inshore boundaries may be moved deeper, for example, if surveys find rooted eelgrass within two vertical feet of the -18 ft MLLW contour. In such cases, only survey data taken within the revised tract boundaries are used in the final estimation of biomass. The side boundaries of a tract may also be expanded -- as in cases where surveyers discover that commercial geoduck densities exist beyond the initial mapped tract -- but in such situations a new map of the expanded tract is required.

Standard Layout of Systematic Grid Lines

Once the tract has been mapped, the beginning points for systematic grid lines of transects are determined and marked with buoys. Each line of transects begins at the -18 ft MLLW contour; this depth is determined in the field with a fathometer and a tidal correction factor from computer generated daily tide graphs for the area. A point along the tract's -18 ft MLLW contour is randomly selected and a heavily weighted buoy is dropped there. Buoys are subsequently placed at 1,000-ft intervals along the entire length of the tract's -18 ft MLLW contour. Distance between buoys is measured with a laser range finder; a band of reflective tape is wrapped around the top of each buoy to facilitate long distance laser fixes. If a laser range finder is not available, or if rough weather precludes its use, buoys may be placed using DGPS fixes. After this initial buoy placement, a diver descends and re-positions the line exactly along the -18 ft MLLW contour, if required, using a digital depth gauge and a correction factor from daily tide graphs for the area. The diver then anchors the buoy line in the substrate with two or three steel reinforcing bars.

Spacing grid lines every 1,000 ft ensures, in theory at least, that no point within the tract will lie more than 500 ft from the nearest surveyed point. There are cases, however, where systematic placement of grid lines results in larger unsurveyed areas. Because grid lines are spaced beginning from a random starting point, the final grid line on one side of a tract may end up, for example, 900 ft from the tract boundary. To make sure that no point on the tract lies more than 500 ft from the nearest grid line, there are three possible solutions in this example: 1) Extend the tract boundary anywhere between 100 and 600 ft, and run another grid line of transects 1,000 ft from the previous line; or 2) Move the tract boundary at least 400 ft closer to the grid line; or 3) Place another grid line of transects anywhere within 500 ft of the existing tract boundary. Since it is often impossible to extend tract boundaries (due to the presence of hazards, closed areas, other tracts, etc.), and because shrinking tract boundaries reduces fishing area, the third solution is used most frequently. For more details, see *Variations on the standard grid line layout* below.

Once buoys have been systematically placed along the -18 ft MLLW contour at 1,000 ft intervals, the buoy positions are mapped. Whenever possible, buoy positions are mapped with a combination of DGPS fixes and laser range-finder fixes. Laser fixes rely on triangulation of laser ranges between the buoy and clearly identifiable landmarks appearing on the DNR-generated maps (e.g., fixed navigational aids, bridges, towers, jetties, docks). The laser range-finder currently used is capable of fixing positions marked with a reflective mirror from as far away as 4.8 km. Figure 4 shows and example of buoy mapping on a geoduck tract. On some tracts, it is impractical to shoot laser ranges to shore; in these cases DGPS fixes may be sufficient.

Once these steps have been taken to map the tract, dive surveys are initiated beginning at each of the anchored buoy lines. A series of 900 ft^2 transects are taken along a compass bearing headed directly offshore from each bouy. Figure 3 shows a typical survey layout with grid lines spaced at 1,000-ft intervals and running directly offshore.

Variations on the Standard Grid Line Layout

On some tracts, the survey layout described above -- systematic grid lines running directly offshore every 1,000 feet along the -18 ft MLLW contour -- requires modification. Variations on the standard layout are sometimes required for one or more of the following reasons:

1. To increase cost-effectiveness of the survey in terms of transects surveyed per unit of diver bottom time.

2. To reduce the likelihood of bias due to nonrepresentative sampling of the tract area.

3. To meet the required standard for statistical precision described above.

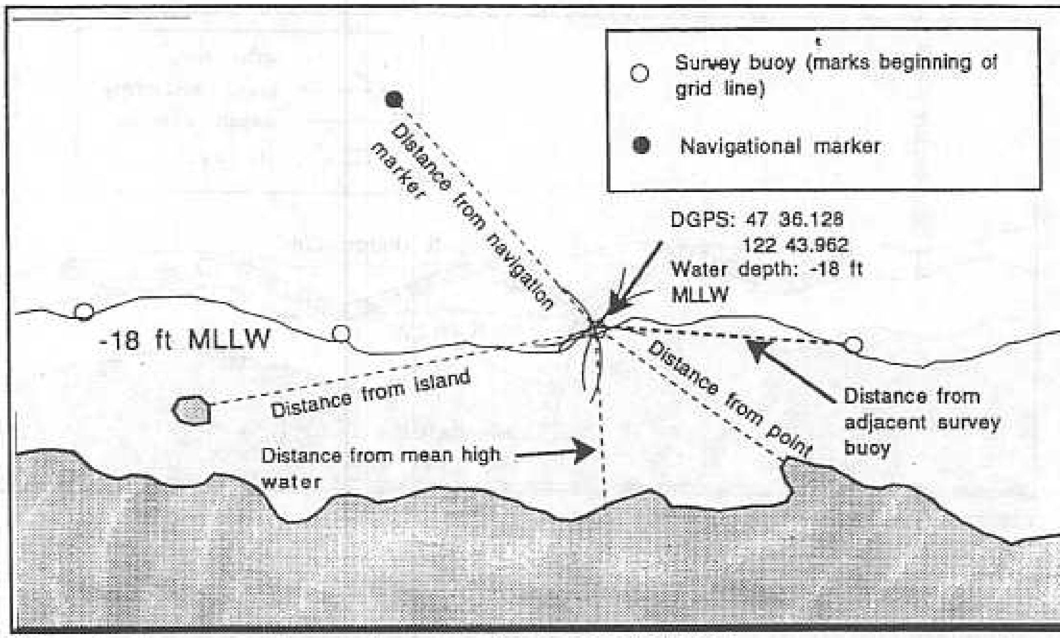


Figure 4. An example of survey buoy mapping on a geoduck tract.

Steep, narrow tracts frequently require a slightly different grid line layout to meet all three of the above goals. On such tracts, the steeply-sloping bottom often allows room for only one 150-ft long transect before divers reach the -70 ft contour. This single transect will require roughly ten minutes of bottom time, only four minutes of which are spent counting geoducks; the other six minutes are used on the descent, ascent, and three-minute safety stop.

In addition to being wasteful, a series of such single transects on a very narrow tract invites bias. This occurs when divers reach -70 ft prior to finishing the transect, and turn to finish the transect along the -70 ft contour. On long, narrow tracts, this may occur so often that a large proportion of the sampling effort takes place along the -70 ft contour. As noted earlier, depth is a known biological gradient with respect to geoduck density (Goodwin and Pease 1991), and transects running parallel to any depth contour are therefore a source of potential bias in the density estimate.

Finally, narrow tracts often fail to produce biomass estimates of the required statistical precision. This is because only one or two transects are possible every 1,000 ft, resulting in a low sample size (unless the tract is extremely long).

To remedy these problems on narrow tracts, grid lines are sometimes placed along oblique or zigzag angles rather than perpendicular to shore. Figure 5 shows examples of oblique and zigzag lines on narrow tracts. Obliques and zigzags allow more back-to-back transects to be surveyed before divers must surface, thus providing more information per unit time, as well as a larger sample size per length of tract shoreline. In the case of zigzag lines, the likelihood of bias is also reduced, because divers immediately turn inshore upon reaching the -70 ft contour, continuing to cut across depth gradients rather than surveying parallel to them.

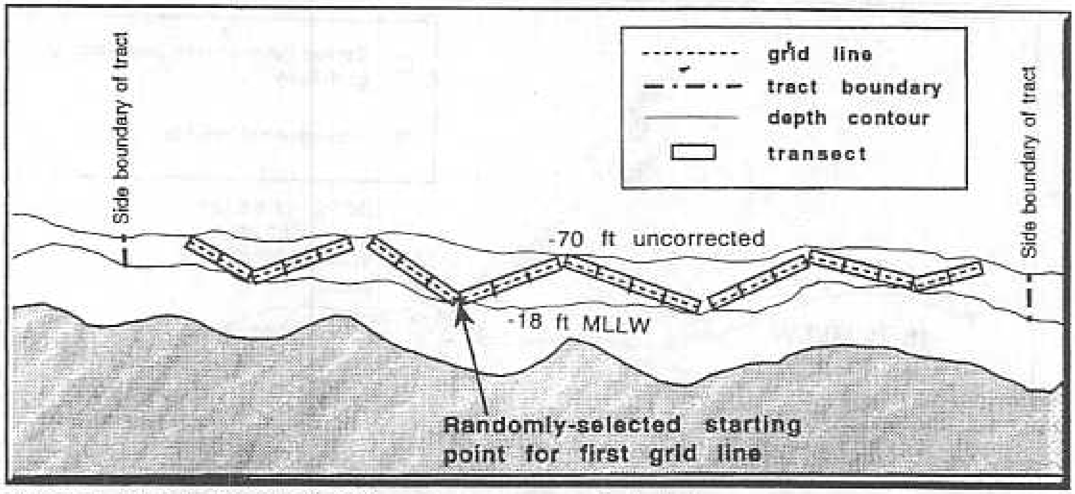


Figure 5. Zig zag layout of grid lines on a narrow geoduck tract.

On some tracts -- usually small tracts, or those with highly variable geoduck density -- grid lines spaced systematically every 1,000 ft do not result in biomass estimates of the required statistical precision. Increasing the sample size (i.e., running more transects) is sometimes the answer. This is accomplished by splitting the existing grid lines -- in other words, running lines of transects every 500 ft rather than every 1,000 ft. Note, however, that to reduce the chance for sampling bias, new grid lines must be run between *all* existing lines rather than a select few. There is no limit on the number of times existing lines may be split in this manner to obtain more transects, but there are diminishing returns with respect to precision as sample size increases.

Strict adherence to systematic spacing of grid lines may sometimes result in samples that are not spatially representative of the tract, and are thus likely to be biased. As noted above, the goal of unbiased surveys is to ensure that no point on the tract lies more than 500 feet from the nearest grid line of transects. Because the grid lines are spaced beginning from a random starting point within the tract (rather than the tract boundary itself), situations may arise in which the final grid line of transects lies more than 500 ft from the tract boundary. As noted above, this is most easily remedied by simply adding another grid line of transects anywhere within 500 ft of the tract boundary. The shape of the shoreline may also require additional grid lines. Figure 6 shows an example in which, due to the shape of the shoreline, a large area of the tract would remain unsurveyed with systematically-spaced grid lines. In this example, the logical (but entirely *ad hoc)* remedy was adding another grid line of transects in the middle of the unsurveyed area, such that no point on the tract lies more than 500 ft from the nearest grid line. Similar *ad hoc* sampling schemes are sometimes called for on tracts with "dog-leg" shorelines, islands, or other unusual geographic contours.

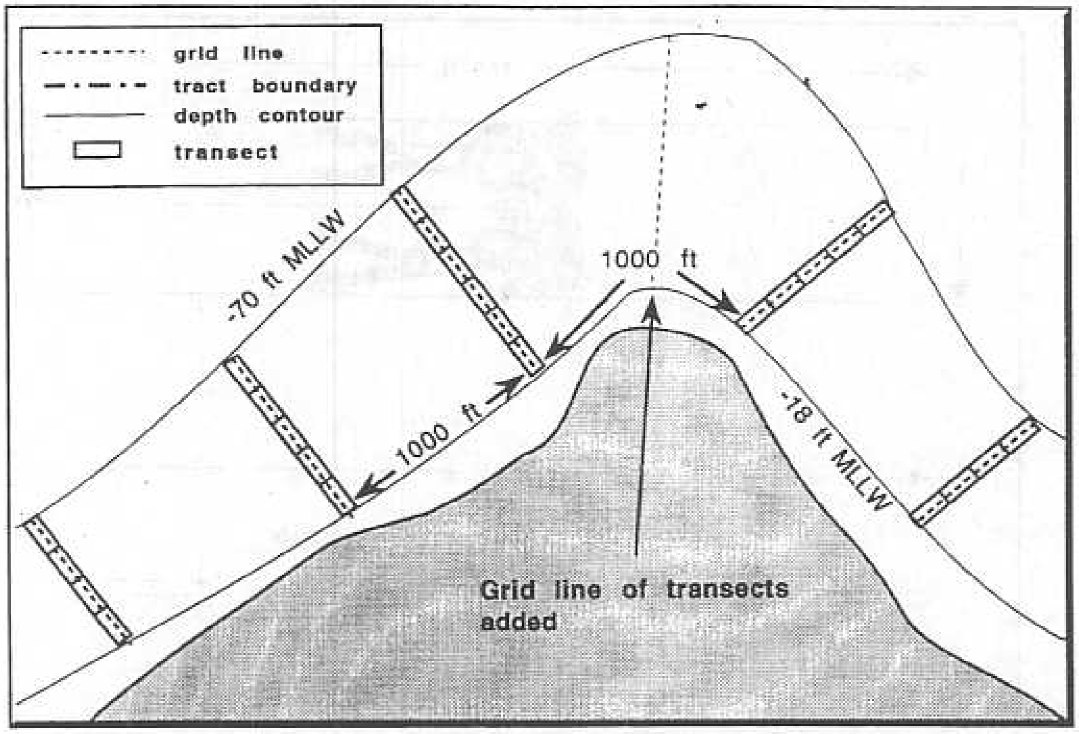


Figure 6. *Ad hoc* placement of an additional grid line of transects to achieve representative sampling of a large area of the tract.

Geoduck Survey Methods

Strip Transect Surveys

To estimate the number of harvestable geoducks within each 900 ft^2 transect, two divers swim side by side, each counting all geoduck siphons, or marks in the substrate which are judged to have been made by geoducks (also called "shows" or "dimples;" see the section *Identification of geoduck shows* below). An individual diver is responsible for counting the geoduck "shows" directly underneath his or her half of the six-ft wide transect rod and spool (Figure 7). Thus, each diver surveys a swath three-ft wide by 150-ft long. The sum of the two diver counts on an individual transect is the total observed number of harvestable geoducks on that transect (d_{obs} in Equation 1 above). In order to ensure consistent transect length and area, the transect line is periodically re-measured to detect and correct any stretch or shrinkage.

An individual diver attempting to survey geoducks in swaths wider than three ft will generally produce unreliable counts, due to the subtle character of geoduck shows and the poor underwater visibility in Puget Sound. Double counting of geoducks may occur when a diver must scan more than three feet in high-density geoduck areas. An additional problem with variants on the historically-used three-ft transect width is that geoduck show factors used in adjusting density have only been estimated on show plots of this width (see *Show plot surveys and show factors* below). Use of a different transect width may invalidate the use of the currently-accepted 0.75 show factor and require additional studies.

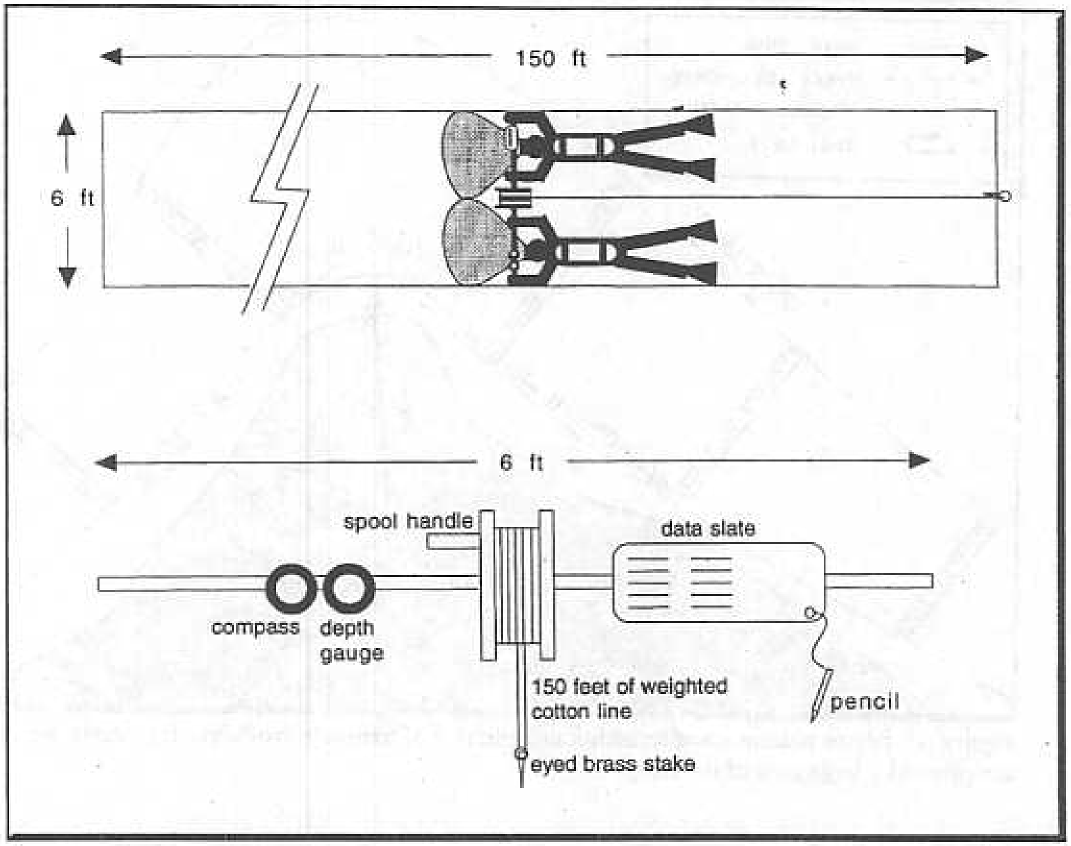


Figure 7. Two divers performing a strip transect survey of geoducks within a 900 square foot transect, and details of the transect pool.

The transect is initiated by planting a metal stake in the substrate which temporarily anchors the 150-ft long transect line. The first transect along any systematically-placed grid line begins at or near the anchored buoy marking that line along the -18 ft MLLW contour (see the section above). A compass course is determined prior to entering the water, generally directing the long axis of the transect perpendicular to the shoreline; oblique or zig-zag courses are sometimes used in surveying extremely narrow tracts as described above. Divers swim along the compass course and away from the shoreline, unspooling the 150-ft transect line as they swim. Each transect typically requires about four to five minutes.

If at the end of the 150-ft line, the -70 ft (uncorrected to MLLW) water depth has not been reached, another transect is initiated along the same compass course. The divers signal the start of each new transect for the boat tender by separating approximately 15-20 ft. One diver remains at the ending point of the transect, recording data for the transect on a dive slate, while the second diver swims back along the transect to respool the transect line. Meanwhile, the tender boat hovers near the divers' bubbles to record the starting position of each transect based on this separation of bubble streams (see *Recording data* below). When the -70 ft water depth is reached, the divers return to the surface and are moved to the next transect buoy to begin another line of transects. If divers reach -70 ft prior to reaching the end of the 150-ft long transect, they turn (generally upcurrent) and finish the transect obliquely toward shore. If a transect ends slightly shallower than the -70 ft contour, divers generally return to the surface; this avoids the potential bias inherent in counting a transect which lies almost entirely along a depth contour.

Lines of such transects are completed at systematic intervals throughout the bed, generally spaced 1,000 ft apart, until the entire bed has been surveyed at a sampling intensity which produces biomass estimates of a specified statistical precision (see the sections *Precision of geoduck biomass estimates* and *Sample size* above).

Identification of Geoduck Shows

Geoduck siphons, when exposed above the surface of the substrate and pumping water, are easily recognized by their large size, elliptical or oblong shape, a flat (rather than rounded) siphon tip, the absence of tentacles along the inner portion of either siphon opening, and the fact that both siphon openings are the same size. When partially retracted, geoduck siphons may be identified by their elliptical or oblong shape, flat siphon tip, and sometimes by the presence of pellet-like particles of undigested particulate matter (pseudofeces) lying on the surface near the siphon tip. Such "dimples" may be probed with thin neoprene finger gloves for verification; geoducks have a characteristically soft, rubbery texture (as opposed to a slimy feel) with no horny plates on the siphon tip. When probed in this manner, geoducks typically retract their siphons slowly.

Subtidal geoduck tracts almost always contain other animals, however, whose siphons or shows may be confused with geoducks by inexperienced divers. These include other molluscs such as horse clams (*Tresus capax* and *T. nuttallii*), false geoducks (*Panomya* spp.), piddock clams (*Zirfaea pilsbryii*), cockles (*Clinocardium nuttallii*), horse mussels (*Modiolus rectus*), and truncated softshell clams (*Mya truncata*), as well as animals from other phyla (retracted sea pens, for example). Density and biomass estimates will obviously be biased if surveyers count these animals as geoducks, or if they fail to count geoducks under the assumption that they are something else.

Figure 8 shows the major differences between geoducks and those of other subtidal molluscs. Harbo (1997) provides an excellent chapter on siphon identification, including a key and color photographs of many north Pacific clam siphons. WDFW staff provide an annual class on geoduck survey methods which includes color slides of clam siphons and a touch tank containing various clam species buried up to their siphons. The class is open on a first-come basis to tribal shellfish biologists and biologists employed by ecological consulting firms.

The animals most easily confused with geoducks during subtidal surveys are horse or "gaper" clams of the genus *Tresus*. Two characteristics of the siphon tip serve to distinguish both species of horse clams from geoducks: 1) The presence of an inner ring of tentacles on the horse clam's siphon, and; 2) The presence of horny plates surrounding the siphon tip of horse clams. The tentacles are obvious when horse clam siphons are open and pumping. When the siphon is closed, or when the tip is not visible, divers with thin neoprene finger gloves can often probe the siphon and feel the horse clam's horny plates. Typically, horse clam siphons are oval or nearly round in cross-section, while geoduck siphons are elliptical. Horse clams generally retract their siphons faster than geoducks when disturbed, expelling a jet of water. Finally, horse clam pseudofeces are thin and stringy rather than pellet-like.

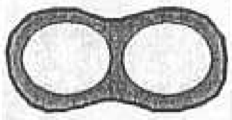
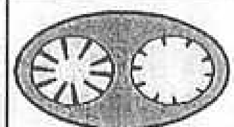
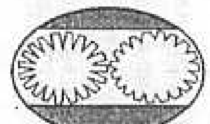
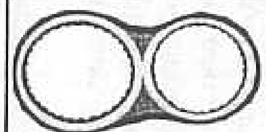
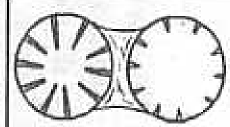
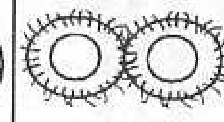
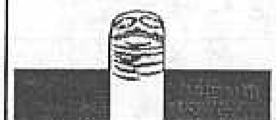
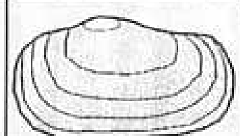
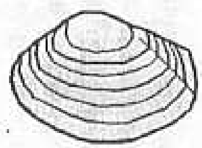
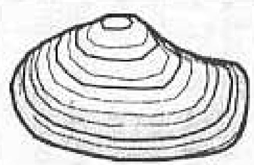
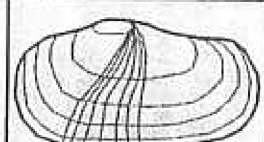
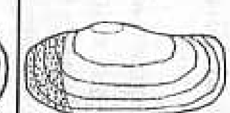
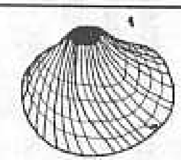
Scientific Name	*Panopea abrupta*	*Tresus sp.*	*Mya truncata*	*Panomya sp.*	*Zirfaea pilsbryii*	*Clinocardium nuttallii*
Common Name	**GEODUCK**	**HORSE CLAM**	**TRUNCATED MYA**	**FALSE GEODUCK**	**PIDDOCK**	**COCKLE**
siphon shape (topview)	 "Double Barrel Shotgun"	 Oval	 Oval	 "Double Barrel Shotgun"	 Bifurcated	 Two Circles
siphon shape (side view)						
tentacles	absent	present/distinct	present/fine	present/very fine	present/distinct	present/distinct
substrate depth	18 to 36 inches	8 to 15 inches	8 to 10 inches	8 to 15 inches	8 to 20 inches	at surface
substrate type	all (except clay)	grvl/cbble/sand	mostly mud/snd	all (except clay)	clay/rock/wood	snd/snd-mud
shell						
siphon color	brown to light brown w/ cream interior	grey/blue tentacles w/ brown exterior	dark brown w/ heavily wrinkled siphon	brown to light brown w/ red and cream circling siphon	mottled reddish and brown with cream white	creamy brown
other distinguishing features	large siphon, smooth/soft, obvious pseudofeces	horny plates on siphon, encrusted plates, hard tip when probed	leathery flaps, index finger shape to siphon	large, thin walled siphon, smooth/soft, different size siphon openings, cleft in shell, obvious pseudofeces	bifurcated siphon, slimy thin feel, toothed shell	"furry" look to siphon, very shallow, heavy round shell

Figure 8. Quick reference for subtidal clam identification.

False geoducks (*Panomya* spp.) are generally smaller than geoducks, and have a distinctive siphon tip with a thin pink or red ring encircling each siphon hole. Even when this color is not apparent, *Panomya* siphon tips appear rounded in side profile, as opposed to geoduck siphon tips, which are box-like when viewed from the side. *Panomya* can also be distinguished by their thinner siphon membranes and because the incurrent siphon, when open and pumping, is noticeably larger than the excurrent siphon. *Panomya* have a barely visible inner ring of very fine tentacles on the siphon.

Mya truncata are usually much smaller than geoducks, and have a thin, dark-brown, wrinkled siphon with leathery flaps at the tip. Piddocks (*Zirfaea pilsbryii*) are easily distinguished from geoducks by their bifurcated (forked) siphons, maroon or dark red siphon tips, and a distinctive white and reddish brown mottled pattern on the siphons. Piddock siphons are also very thin-walled and have a slimy, smooth feel unlike the rubbery siphon covering of geoducks. Piddocks are boring clams, and are therefore found only in substrates such as clay and wood, although this may not be readily apparent if there is a thin surface layer of sand or mud. Cockles (*Clinocardium nuttallii*) are readily distinguished by their white, "furry" siphon tips; they can also be easily dug by hand to verify their identity, since they do not burrow deeply into the substrate. The siphon of the horse mussel (*Modiolus rectus*) appears as one or two narrow slits, usually in muddy substrates. Because the shell lies immediately below the substrate, they are easy to verify by hand-digging.

Non-molluscans such as sea pens (*Ptilosarcus gurneyii*) can sometimes produce a geoduck-like "dimple" when they are retracted into the sand. When probed, they feel soft to the touch like a geoduck siphon. But because sea pens have no siphons, they cannot retract further into the substrate when probed by hand. When visible, sea pens are a distinctive bright orange color.

The field experience of surveyers is crucial when distinguishing geoduck shows and siphons. New WDFW surveyers gain such experience in part by making practice "surveys" with experienced biologists, and by positively verifying their siphon identifications with dig samples. When making transect counts, WDFW surveyers include only shows which can be readily identified as belonging to a geoduck.

Recording Data

At the start and finish of each transect, the divers record water depth (i.e., ambient depth uncorrected to MLLW) to the nearest ft using a digital depth gauge. At the end of the transect an assessment of the surface substrate composition is recorded. The substrate is assigned one or a combination of the following categories: mud (<63 microns), sand (63 microns-2 mm), pea gravel (2-20 mm), and gravel (>20 mm). Particle sizes and the dominant substrate throughout the length of the 150-ft transect are judged subjectively by the surveyers, and are not quantitatively measured with traditional screening techniques. Cobble, boulders, logs, wood debris, and other features associated with the substrate (e.g., sandy hummocks) are also recorded when present. The presence of readily visible macro flora and fauna is also recorded, including eelgrass, major algal groups, major epibenthic animals, and fish. The boat operator, hovering above the divers' bubbles at the start of each transect, records DGPS latitude and longitude to the nearest thousandth of a minute. Starting time for each transect is also recorded, so that the uncorrected transect depth reported by the divers may be later corrected to MLLW with the use of a tide graph for the area. DGPS latitude and longitude are also recorded at the end of the final transect in any line of continuous transects.

Appendix 1 contains sample data sheets. Appendix 2 lists the codes used for recording substrate composition and associated plant and animal data.

Geoduck Dig (Weight) Samples

As noted earlier, cluster samples of geoducks (called dig samples) are taken systematically at every sixth transect previously surveyed for density. Transects where the density of geoducks falls below currently accepted commercial levels (i.e., <0.04 geoducks per ft^2) are eliminated from this selection process. The dig samples provide an estimate of mean weight per geoduck (Equation 4), as well as information on market quality, difficulty of digging, and substrate composition below the surface layer.

Using DGPS fixes and corrected depth data from the transect surveys, the boat is anchored near the middle of each systematically-selected digging transect. A single line-tended diver descends immediately below the boat and haphazardly digs the first ten visible geoducks. The diver also records information on the surface substrate composition, the water depth at which geoducks were dug, and a subjective evaluation of the ease or difficulty of digging. The boat crew records DGPS latitude and longitude of the digging location, the number and condition of geoducks dug, and the time taken to dig the samples. The geoducks taken at each transect are kept separately in moist burlap sacks labeled with the transect number, and are periodically soaked with seawater to keep them alive. Appendix 1 contains an example of the data recorded for a typical dig transect.

The geoduck samples are kept cool and moist in burlap sacks, transported to the Point Whitney Shellfish Laboratory, and either processed the same day or placed in running sea water for later processing. Processing occurs as soon as possible to avoid mortalities which may result from injuries sustained during digging. Whole wet weight (grams) is measured after a drainage time of a few minutes to two hours. All geoducks are weighed, but damaged clams -- those with broken valves or tissues blown apart by the water jet -- are noted and eliminated from the calculation of mean weight. The greatest anterior-posterior length of the right valve is measured with calipers to the nearest mm. The right valve is the valve on the observer's right side when the clam is held with the siphon down and the umbo facing the observer (Figure 9). The siphon is then cut from the body (Figure 9) and weighed separately. Siphon weight information is valuable for commercial marketers, since the siphon is the portion of the geoduck which currently determines the market price in many cases. Overall geoduck quality, which is a function of gross appearance, color, and size, is then judged as either commercial or non-commercial. Appendix 1 shows an example of typical weight and quality data as recorded on the data sheet.

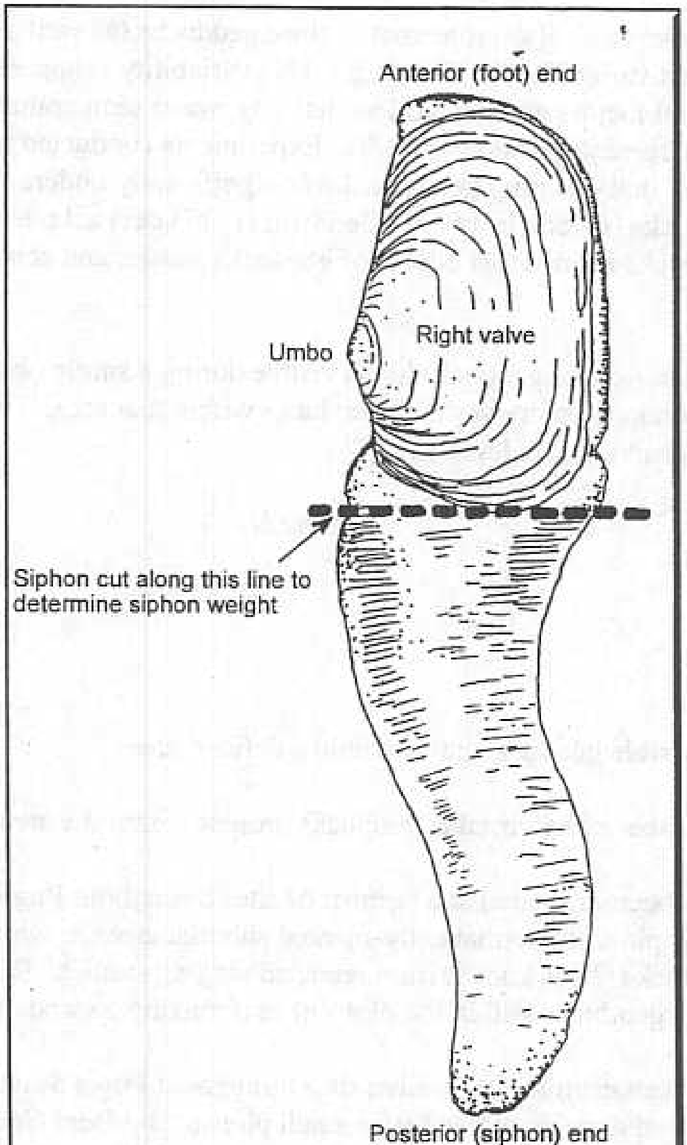


Figure 9. Geoduck clam.

Show Plot Surveys and Show Factors

A geoduck "show" is either a geoduck siphon visible above the substrate surface or a depression left in the substrate which can be identified as having been made by a geoduck siphon (Goodwin 1973). The only practical way to estimate geoduck density is to count such "shows" within measured transects. Digging numerous samples from the substrate, a method commonly employed to estimate the density of small intertidal clam populations, is not feasible for geoducks on a large spatial scale because they are buried too deeply in the substrate.

Counting shows, however, is also problematic, since geoducks (as well as other clam species, see Flowers 1973) exhibit variability in "showing." This variability is apparently a function of various environmental factors such as food availability, water temperature, substrate type, algae cover, turbidity, and currents (Goodwin 1977). Experiments conducted in Washington in the early 1970s indicated that counting geoduck shows significantly underestimated the true density of harvestable geoducks (Goodwin 1973). Goodwin (1977) devised methods of estimating the true density of geoducks from visual counts of geoducks shows, and coined the term "show factor."

The show factor is the ratio of geoduck shows visible during a single observation of any defined area and the true abundance of harvestable geoducks within that area. The show factor (S) is expressed as a proportion, and calculated as

$$S = n / N \quad . (9)$$

where

S = show factor

n = the number of visible geoduck shows within a defined area

N = the absolute number of harvestable geoducks present within the area

This proportion has been estimated at a number of sites throughout Puget Sound with the use of "show plots." Show plots are permanently-marked subtidal areas in which the absolute number of harvestable geoducks (N) is known from repeated tagging studies. Divers then revisit the plot and count all visible geoducks within the plot (n) as if making a standard survey.

Show factors have been estimated at twelve sites throughout Puget Sound from 1984 to 1993. Goodwin (1977) found a seasonal trend with small plots at Big Beef Creek, Hood Canal, where zero or few geoducks were observed between the months of October and March. The average monthly geoduck show factor from the twelve sites in Puget Sound reached an average maximum for March of 0.73 (i.e., only 73% of the geoducks present would be expected to be observed during an instantaneous count by divers). There were small incremental declines each month to 0.54 in September and to 0.43 in October. Show factors also vary from year to year. For example, the average annual geoduck show factor for all show plots in 1986 was 0.51. In 1992, the average annual geoduck show factor for all show plots was 0.77. The Puget Sound average show factor for all show plots from 1984 to 1993 is 0.62.

Since establishing show plots for a tract is extremely time consuming, state and Tribal managers have agreed to use a show factor of 0.75 to estimate biomass for pre-fishing surveys on a given tract. In other words, we assume that 75% of the harvestable geoducks present are actually seen and counted during an instantaneous transect count. Using a standard show factor avoids the time and expense of establishing separate show plots for each tract being surveyed. A show factor of 0.75 is, for most tracts, conservative and will not lead to overestimation of geoduck biomass on a given tract. A show factor of 0.75 is used to estimate density on all tracts for pre-fishing surveys, unless there is a show plot established for a tract that will give site-specific data.

Some situations may arise in which surveyers may wish to establish a show plot despite the cost and time involved. Examples include: 1) Surveys carried out in habitats or depths for which no historical show plot data exist; 2) Surveys where risk-averse management policies dictate that a conservative (i.e., low) show factor be used (as, for instance, when geoduck densities below a certain threshold would permit developers to destroy a potentially commercial geoduck tract); 3) Surveys using non-standard methods (e.g., quadrat counts, transects more or less than three feet in width); and 4) Surveys carried out by inexperienced divers who wish to verify their counts. The following paragraphs describe the field methods used to establish and count a show plot.

Show plot surveys are carried out during the period March 1 - October 14, when geoducks are actively pumping water and the the show factor is highest. Show plot counts made during the fall and winter are likely to underestimate the actual number of geoducks present within the plot because of the documented low show factor (Goodwin 1977), or else would require unreasonable effort and time to be certain that all geoducks within the plot had been detected.

Show plot sites are selected so that they are close to the tracts or areas being surveyed and to mimic, as closely as possible, the substrate and current conditions of the survey tract or area. Obviously, show plot sites must contain geoducks in roughly commercial densities. Show plots are usually situated along a depth contour which is midway between the depths being surveyed at the nearby tract or area. For example, most show plots for commercial geoduck surveys, which take place between the -18 ft MLLW and -70 ft contours, are situated at the - 40 ft MLLW depth. To avoid destruction of the show plot boundary markers, show plots are not sited in areas where boats frequently anchor or where tidal currents sweep large amounts of algae along the bottom. Finally, show plots are not sited in areas with large populations of horse clams (*Tresus* spp.), which might confound the results.

Once a suitable site has been chosen, yellow polypropylene lines are staked on the bottom to delineate a standard 900 ft^2 geoduck transect, including a line down the center of the six-ft wide transect. In this way, two three-ft wide strips running for 150 ft are outlined with yellow line. Corners of the plot are staked with steel reinforcing bar, and the line is staked at intervals with smaller metal stakes to prevent the line from floating above the substrate.

Following placement of the plot boundary markers, divers begin "tagging" all geoducks which are showing within the plot. Two divers slowly swim the entire plot, each diver being responsible for his or her three-ft wide half of the plot. Geoduck shows are tagged by placing a sturdy wire stake -- usually 3/16 inch diameter and 12 inches in length -- next to the siphon. All such tags are oriented to either the left or right of the siphon to avoid confusion with other shows, and are carefully placed about 1.5 inches from the siphon to reduce the risk of injury to the animal. Tags are set roughly six inches into the substrate wherever possible. During tagging, divers situate themselves perpendicular to their half of the plot to prevent fins from dislodging tags that are already in place.

All geoduck shows are tagged in this manner throughout the show plot over a period of several days. Following each tagging session, divers record the total number of tags placed. Each successive tagging session requires fewer new tags, in the manner of classic "removal sampling" methods (Zippin 1956; Seber 1982). In this case, geoducks are "removed" by tagging, and we assume that the entire population within the plot has been censussed when, after several repeated tagging sessions, no new tags are required. This point is generally reached after about five days in most geoduck show plots, although tagging must continue as long as new shows are discovered during the previous tagging session. Several tagging sessions are sometimes done during a single day to speed up the "removal" process (i.e., to reach the point where repeated sessions encounter no new shows). However, repeated tagging sessions during the same day run the risk that at least some geoducks will not show because they have been disturbed by the divers, and therefore tagging should span a minimum of three days. To avoid bias of this sort, the final determination of complete "removal" is made on a day when no previous tagging sessions have occurred.

After repeated tagging sessions result in no new shows, divers carefully gather all tags from the plot and the total number of tags from both halves of the plot is assumed to represent N, the absolute number of harvestable geoducks within the plot.

Once N has been established, it is possible to estimate show factors by returning to the plot and counting the number of shows as if surveying a standard 900 ft^2 transect. Without disturbing geoducks, two divers locate the show plot and begin a routine transect survey, using the polypropylene line boundaries rather than the transect spool to delineate the transect. Each diver swims his or her half of the plot at a speed which is consistent with the swimming speed during normal transect surveys (roughly 4-5 minutes for a 150 X 6 ft transect), counting all shows. The total number of shows (n) is divided by N (known from the repeated tagging done previously) to produce the estimated instantaneous show factor (S) as in Equation 9. Site specific show factors may be estimated in this way for successive days, weeks, or months; estimates after a year run the risk of bias due to changes in the geoduck population within the plot (N) due to recruitment or mortality. In estimating show factors on a daily basis, divers are rotated to reduce the chance of bias from an individual diver remembering the location of certain geoducks within the plot (Goodwin 1977).

Seasonal Considerations for Geoduck Surveys

State and Tribal managers have agreed that geoduck surveys will not made from October 15 through February 28, due to the low "show factor" of geoducks during the winter months (Goodwin 1977). Surveys made during this period of time would tend to produce highly unreliable density estimates; see the section *Show plot surveys and show factors* above.

Eelgrass Surveys

Eelgrass (*Zostera marina*) provides important habitat for juvenile Dungeness crab, spawning herring, and other marine animals. The WDFW Habitat Division requires that geoduck harvest not occur within eelgrass beds. Prior to fishing, eelgrass associated with geoduck beds is surveyed and a two foot vertical buffer is established around occurrences of rooted eelgrass. On a tract where the slope is very slight, using this standard two-ft vertical buffer may needlessly exclude large portions of the commercial tract. Under these circumstances, a 180-ft horizontal buffer (seaward and deeper than the deepest eelgrass) may be used. Geoduck harvest is not allowed within these buffer zones. Thus, eelgrass surveys are an integral part of every pre-fishing geoduck survey, because eelgrass distribution determines the inshore or shallow boundary of the geoduck tract in many cases. This inshore boundary is required for a determination of total surface area, used in Equation 6 to estimate total geoduck biomass on the tract.

To determine whether the standard two foot buffer zone below eelgrass impinges on a commercial tract's inshore boundary (normally set at -18 ft MLLW), pre-fishing eelgrass surveys are conducted by divers swimming along the -16 ft MLLW contour. Occurrences and extent of eelgrass found deeper than -16 ft MLLW are noted using DGPS latitudes and longitudes. When eelgrass occurs deeper than -16 ft MLLW, divers characterize the occurrences, define the perimeter of eelgrass beds, and note the water depth at the deepest occurrence of eelgrass for that site. Normally a two foot vertical buffer along the entire length of the tract is set below the deepest occurrence of any rooted eelgrass found along the tract. Alternatively, a buffer zone of at least 180 ft around eelgrass beds deeper than -18 ft MLLW can be used when the tract is marked to exclude eelgrass and the marking is visible to divers within the tract.

Labor Costs of Geoduck Surveys

Table 3 shows the field time spent surveying geoducks at four recently-surveyed tracts, and provides a rough planning guide. Survey time includes not only running transects and digging geoduck samples, but also includes boat transit to and from the tract, boat maintenance, eelgrass surveys, and the placement and mapping of buoys which mark the sample grid lines. Laboratory time (weighing geoduck samples) and the time required for data entry and analysis, however, are not included here.

Table 3. Time budget (in person-hours) for geoduck field surveys at four commercial tracts.

Tract	Size (acres)	Transects / Acre	Transect Survey Time (hrs)	Dig Sample Time (hrs)	Tract Mapping Time (hrs)	Eelgrass Survey Time (hrs)	Boat Maintenance Time (hrs)	Transit Time (hrs)	Total Time (hrs)	Hours / Acre
Agate Pass	945	0.34	404	128	52	64	48	12	708	0.75
Jamestown	300*	0.36	164	24	4	64	20	12	288	0.96
Olele Pt	160	0.59	174	56	28	48	4	12	322	2.01
Pt Robinson East	22	1.18	44	12	4	0**	0	12	72	3.27

* The data for this tract represent an initial survey area.
** Eelgrass surveys were not performed at this tract because the inshore tract boundary for non-Indian divers was roughly -35 ft MLLW throughout the tract, well below the deepest occurence of eelgrass in Puget Sound.

As shown in Table 3, transect surveys consume most of the total geoduck survey time. Transect surveys required between 54 - 61% of the total survey time at the four tracts. Note that the "transect survey time" in Table 3 includes not only actual diver bottom time, but also include all hours worked by the non-diving team aboard the boat, time spent during surface intervals, time spent suiting up, recording data, and other miscellaneous "diving" tasks which do not actually occur underwater.

Table 3 also suggests that as tract size decreases, the survey time required per unit of surface area increases. This occurs primarily because small tracts require more transects per acre to reach the statistical precision requirements (see *Sample size* above).

Surveys are usually conducted by four divers. A team of two divers begins the day by running transects until their no-decompression bottom time is expended. Meanwhile, the two remaining divers operate the boat, keep track of the divers, and record position and time data for the transects. The second team continues transect surveys while the first team completes a surface interval. Following the surface interval and the ascent of the second team, the first team typically re-enters the water to continue transects until their bottom time is expended. Digging typically requires one diver who actually digs the geoduck samples and at least two crewpersons who operate the boat, water pump, safety line, and record data.

Bottom times for WDFW divers must comply with the US Navy Tables, and each ascent must include a mandatory three to five-minute safety stop at -15 ft. Therefore, divers who utilize computers or who do not make recommended safety stops would obviously require less time to complete transect surveys and dig geoduck samples than WDFW divers.

Environmental Assessment

Geoduck beds which prove to have commercial concentrations of geoducks are then further studied. Inquiries are made to various agencies and groups to obtain additional ecological information, and to learn of possible interaction between geoduck fishing and other uses of the areas.

Washington Department of Ecology is contacted for water quality information. Divisions within WDFW and local Tribes are contacted to learn of sensitive habitats, important resources, or activities that may be affected by geoduck fishing. The county in which the proposed fishing will occur is contacted to learn of the shoreline designation of areas adjacent to geoduck beds. After receiving comments from all of the groups contacted, an environmental assessment is written by WDFW for each proposed geoduck fishing location.

The environmental assessment describes the size and location of the proposed tracts. Tract substrates and water quality are summarized, as well as the geoduck abundance, size, and quality. Other biota including fish, invertebrates, aquatic plants, marine mammals, and birds are discussed. The last part of the assessment covers activities including fishing, navigation (boat traffic), and other uses.

DNR then writes an adoption notice and notifies shoreline owners and other members of the public of the planned fishery.

Part II Equilibrium Yield Modeling

Methods

Data

Over 2,000 geoducks were sampled between 1979 and 1981 at 15 previously unharvested sites in Puget Sound and the Strait of Juan de Fuca to obtain information on age distribution and growth (Figure 10). The sites span four of the current six geoduck management regions, with six sites in the Hood Canal region, two sites in the Central Sound region, one site in the Strait region, and two sites in the South Sound region. Samples were taken randomly within each site at depths of -30 to -60 ft MLLW by washing geoducks from the substrate with a commercial water jet. Age was determined from annual growth increments in the hinge plate using the acetate-peel method (Shaul and Goodwin 1982). The von Bertalanffy growth parameters (L_∞, k, t_0) were estimated for each of 234 sub-sampled geoducks with a nonlinear regression method. A two-factor ANOVA was used to test if growth parameters differed within or between management regions. Hoffmann *et al.* (1999) provide a detailed description of the growth analysis.

Equilibrium Yield Model

Geoduck yield was modeled using a deterministic, age-structured equilibrium yield model. Given a set of parameter estimates for mortality, maturity, growth, and selectivity, the model collapses the number of geoducks at age for all cohorts in the population to a single cohort, assumed to represent the stable age distribution of the population. Population size was based on an initial unfished spawning population, a declining exponential function for survival at age, and by the Baranov catch equation. The model assumed continuous recruitment, the magnitude of which was based on a Beverton-Holt stock-recruitment relationship. Fishing mortality (F) was stepped from zero to a specified upper limit while computing yield per recruit (YPR) and spawning biomass per recruit (SPR) for each value of F. The model was constructed as a QuattroPro for Windows (Version 5.0) spreadsheet.

The model required the following user supplied inputs:

1. An instantaneous rate of natural mortality (M)
2. A shape parameter value for the Beverton-Holt S-R relationship (A)
3. The unfished ("virgin") spawning biomass ($B0_s$) in kg (only required to scale absolute biomass)
4. The fishery selectivity coefficient at age (v)

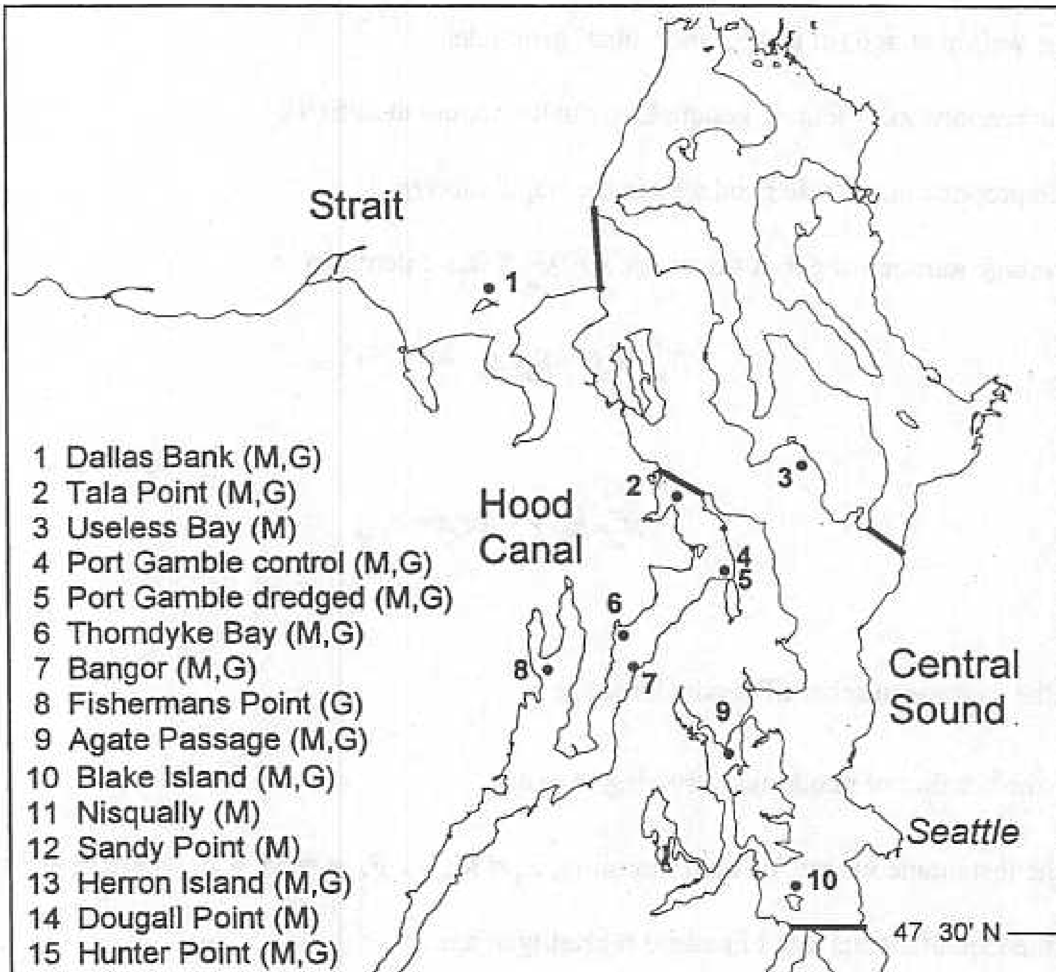


Figure 10. Sampling sites for geoduck natural mortality and growth.

5. The weight at age (in kg) for individual geoducks

6. The proportion of female geoducks sexually mature at age (Φ)

7. The proportion of male geoducks in the population (p_m)

The average number of geoducks at age a ($\overline{N_a}$) was calculated as

$$\overline{N_a} = N_a(1 - S_a)/Z_a \quad \text{for } a < a_{\max} \tag{1}$$

and

$$\overline{N_a} = N_a/Z_a \quad \text{for } a = a_{\max} \tag{2}$$

where

$\overline{N_a}$ = the average number of geoducks at age a

N_a = the number of geoducks surviving to age a

Z_a = the instantaneous rate of total mortality, $Z_a = M_a + v_a F$, or $= M_a + F_a$ where $F_a = F\, v_a$

M_a = the instantaneous rate of natural mortality at age a

F = the instantaneous rate of fishing mortality for fully selected age classes, i.e., $v_a = 1$

F_a = the instantaneous rate of fishing mortality at age a (= F v_a)

v_a = the selectivity coefficient at age a

S_a = the annual rate of survival, $S_a = \exp(-Z_a)$

a_{max} = the maximum modeled age of a geoduck in the population

The maximum age (a_{max}) in the model served as an "accumulater age" category which encompassed all ages $a \geq a_{max}$. The assumption implicit in this formulation is that no significant changes in growth, weight, maturity, or selectivity occurred beyond a_{max}. In the case of geoducks, this assumption was reasonable and is addressed below. For other applications, the model spreadsheet could be simply extended to accommodate an unlimited number of older age classes.

For the first age class (a = 1), the number of geoducks surviving to age a (N_a) was calculated as

$$N_a = p_m \text{ for males} \tag{3}$$

and

$$N_a = 1 - p_m \text{ for females,} \tag{4}$$

where p_m was the proportion of males in the population.

For $a > 1$, the number of geoducks surviving to age a (N_a) was calculated as

$$N_a = N_{a-1}\, S_{a-1} \tag{5}$$

The average biomass (in kg) of geoducks at age a ($\overline{B_a}$) was calculated as

$$\overline{B_a} = \overline{N_a} w_a \tag{6}$$

where

w_a = the weight (in kg) of an individual geoduck at age a

Weight at age a was calculated from an allometric length-weight relationship of the form $w_a = xL_a^y$, where L_a = shell length (in cm) at age a, and x and y were constants. Length at age was based on the von Bertalanffy growth equation:

$$L_a = L_\infty [1 - \exp^{-k(a-t_0)}] \tag{7}$$

where L_a = shell length of a geoduck at age a, and L_∞, k, and t_0 were estimated parameters.

Yield per recruit (in kg) at age a (YPR_a) was calculated as:

$$YPR_a = \overline{B_a}\,(F\, v_a) = F\, \overline{B_a}\, v_a \tag{8}$$

Total yield per recruit (in kg) for all ages (YPR) was calculated as:

$$YPR = \sum_a \overline{B_a}\,(F\, v_a) = F \sum_a B_a\, v_a \tag{9}$$

Spawning weight per recruit (in kg) at age a (SPR_a) was calculated for females only as:

$$\mathrm{SPR}_a = \overline{B}_a \Phi_a \qquad (10)$$

Total spawning weight per recruit (in kg) for all ages (SPR) was calculated as:

$$\mathrm{SPR} = \sum_a \overline{B}_a \Phi_a \qquad (11)$$

The fraction of the unfished spawning stock biomass remaining at a given level of fishing mortality (P) was a parameter of the Beverton-Holt spawner-recruit relationship, such that

$$P = 1 - (1/A)\,(1 - \mathrm{SPR} / \mathrm{SPR0}) \qquad (12)$$

where

A = the shape or "steepness" parameter of the Beverton-Holt spawner-recruit function, a user-supplied input ($0 \le A \le 1$)

SPR = total spawning weight per recruit (in kg) from equation 11 above

SPR0 = total spawning weight per recruit (in kg) from equation 11 above when F = 0 (i.e., unfished spawning weight per recruit)

Spawning biomass (B_s) in kg when F > 0 was calculated as:

$$B_s = P\,B0_s \qquad (13)$$

where

P = the parameter in the Beverton-Holt S-R function which represents the fraction of the unfished spawning stock remaining at a given level of fishing mortality (see equation 12 above)

$B0_s$ = unfished spawning biomass in kg, a user-supplied input

Recruitment to the fishery (R) in numbers was calculated using the re-parameterized form (Kimura 1988) of the Beverton-Holt spawner-recruit relationship, such that

$$R = (B_s / \mathrm{SPR0}) / [1 - A\,(1 - P)] \qquad (14)$$

where

B_s = spawning stock biomass in kg when F > 0 (equation 13 above)

SPR0 = unfished spawning weight per recruit in kg (i.e., when F = 0)

and A and P were parameters of the Beverton-Holt spawner-recruit function as described above.

Yield (Y) in kg was calculated as the product of total yield per recruit (in kg) and the number of recruits:

$$Y = YPR\,(R) \tag{15}$$

The model is capable of returning a suite of fishing mortality benchmarks, such as F_{max}, $F_{0.1}$, and $F_{xx\%}$. For example, the fishing mortality rate which produces, over the long run, the maximum yield per recruit corresponds to the F_{max} strategy, whereas $F_{0.1}$ represents a rate of harvest less than F_{max} (Deriso 1987, Gulland 1968).

The fraction of the unfished spawning weight per recruit remaining at a given level of fishing mortality was calculated as SPR/SPR0, and is achieved at a corresponding fishing mortality rate $F_{xx\%}$ where xx represents the ratio (SPR/SPR0)100 . Model predictions of this fraction formed the basis for SPR-based fishing strategies. For example, the fishing mortality rate which resulted in a value of SPR/SPR0 = 0.35 corresponds to the $F_{35\%}$ strategy.

The harvest rate (μ) for fully selected age classes (i.e., when $v_a = 1$) when fishing and natural mortality operate concurrently (Ricker 1975) was calculated as:

$$\mu = F/Z\,[1-\exp(-Z)] \tag{16}$$

Parameter Estimates

Parameter estimates used in the equilibrium yield model are shown in Tables 4 and 5. The derivation of these parameter estimates is described below.

Table 4. Geoduck life history parameters held constant for all study sites.

Category	Parameter	Value
Spawning stock biomass when F = 0	$B0$,	100,000 kg
Instantaneous natural mortality rate	M	0.0226
Length-weight relationship	x	0.349127
	y	2.972807
Maturity (simple logistic)	x	-1.9
	y	9.5
Fishery selectivity (simple logistic)	x	-1.5
	y	8.0
Beverton-Holt shape parameter (Eq. 14)	A	1
Proportion of males in population	p_m	0.5
Maximum (accumulator) age	a_{max}	25

Natural Mortality

The instantaneous rate of natural mortality (M) was estimated from the geoduck age-frequency distribution at 14 of the 15 sample sites (Figure 10) using two different catch curve models (Robson and Chapman 1961; Ricker 1975). Both models assume that mortality is constant for all ages used in the catch curve. The Robson and Chapman model is based on a geometric distribution and assumes that year class survival and recruitment are constant and all ages are equally selected. Geoducks are extremely long-lived, so that the number of animals observed in each one-year age class is typically low, even for sample sizes in which $n > 1{,}000$. Despite this problem, we chose to preserve the data in one-year age classes rather than aggregating ages, a procedure which potentially ignores real variability in the original data and may slightly inflate estimates of M (Noakes 1992). It was not possible to estimate site-by-site mortality rates using catch curves, because no individual site contained enough data to construct reliable catch curves. Age frequencies were therefore pooled from all 14 sites in order to create the catch curve.

To avoid arbitrary choices of the upper and lower ages used in the catch curve "right limb," we established a protocol for data inclusion: The initial upper age limit for the catch curve was the first age at which our sample contained no geoducks (i.e., the first gap in frequency). We then excluded younger age frequencies if they were identified as outliers by Weisberg's (1985) outlier test. Two methods were used to select the lower age limit for the catch curve: 1) The chi-square procedure described in Robson and Chapman (1961) was used to differentiate partially selected ages; and 2) Catch curve regressions were calculated for all possible lower age limits, and we used an *ad hoc* procedure to optimize the coefficient of determination (r^2) and the linearity of positive and negative residuals plotted against age. Once the lower and upper age limits for the catch curve were identified, a chi-square formula was then used to test goodness of fit of fully-selected ages to a geometric distribution (i.e., the Robson and Chapman model).

Sampled geoducks from the 14 previously-unfished sites ranged in age from 2 to 131 years (Figure 11A). The mean age of geoducks was 46 years (SE = 0.56, n = 2,157). The initial upper age limit for the catch curve was 110 years, because no 111-year old geoducks were in our sample. Examination of residuals showed a single large negative residual at the 99-year age class (only one geoduck of this age was in our sample), and this age class was eliminated from the analysis as an outlier, based on the test given in Weisberg (1985). Both the Robson and Chapman (1961) chi-square procedure and our *ad hoc* optimization procedure identified age 28 as the lower age limit for the catch curve. A chi-square was used to test goodness of fit of fully-selected ages (28-98) to a geometric distribution. The resulting chi-square was highly significant ($\chi 2 = 326.56$, df = 68), indicating that the age frequency was not geometric in distribution, and that data requirements for the Robson and Chapman model were not met. Ricker (1975) pointed out that in most stocks, difference in year class strength is the major source of variability, in which case the best estimate of survival would be obtained from a catch curve analysis with equal weighting. The Ricker catch curve based on ages 28 - 98 (Figure 11B) produced an estimate of $M = 0.0226\ y^{-1}$ (± 0.0018 SE, n = 71, $r^2 = 0.70$).

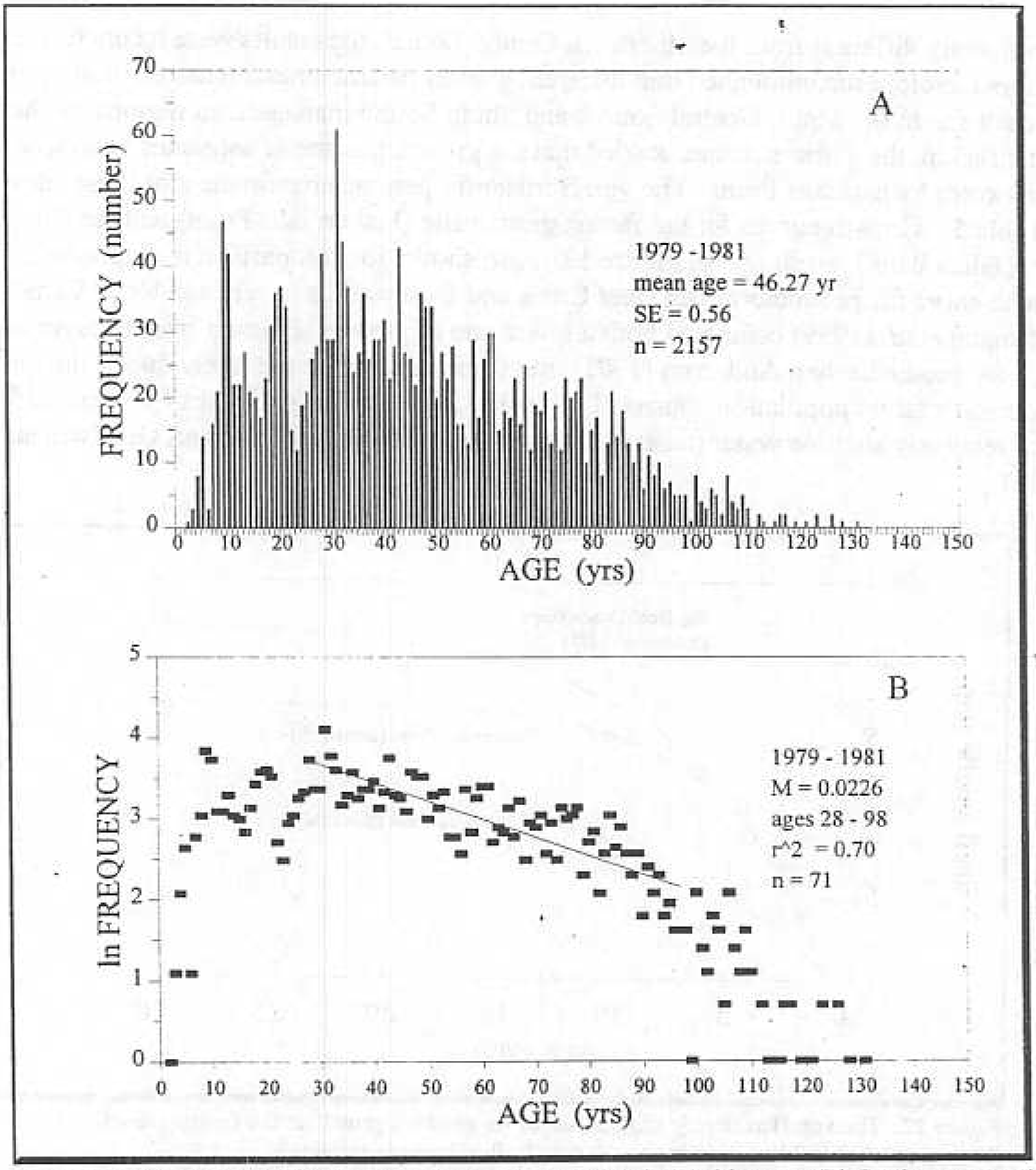


Figure 11. (A) Age frequency geoducks sampled at 14 sites in Washington. (B) Catch curve used to estimate the instantaneous natural mortality rate (*M*) for geoducks.

Growth

Of the three von Bertalanffy growth parameters, only one significantly influenced model-derived target fishing mortality rates: the growth constant *k* (Hoffmann *et al.* 1999). Statistically significant differences in *k* were detected among most of the sites within 3 management regions: Central Sound, Hood Canal, and South Sound. Further testing showed that in South Sound, the sites were also significantly different. In Hood Canal, only one site (Fishermans Point) was significantly different from the others. In Central Sound, the results were inconclusive. The authors therefore recommended that different growth parameter estimates be used as model input for each site in the Strait, Central Sound, and South Sound management regions; in the Hood Canal region, the authors recommended that the growth parameter estimates be averaged for all sites except Fishermans Point. The von Bertalanffy parameter estimates for these sites are shown in Table 5 . Growth curves for the fastest growth site (Fishermans Point) and the slowest growth site (Dallas Bank) are shown in Figure 12. Also shown for comparison is Anderson's (1971) growth curve for geoducks at Big Beef Creek and Dosewallips beaches in Hood Canal. Hoffmann *et al.* (1999) estimated both a lower rate of growth (k) and a smaller asymptotic size (L_∞) for geoducks than Anderson (1971), but these differences are likely due to the fact that Anderson's target population consisted of young, fast-growing geoducks (<5 years old) sampled from relatively shallow water (where mean geoduck shell length is larger; Goodwin and Pease 1991).

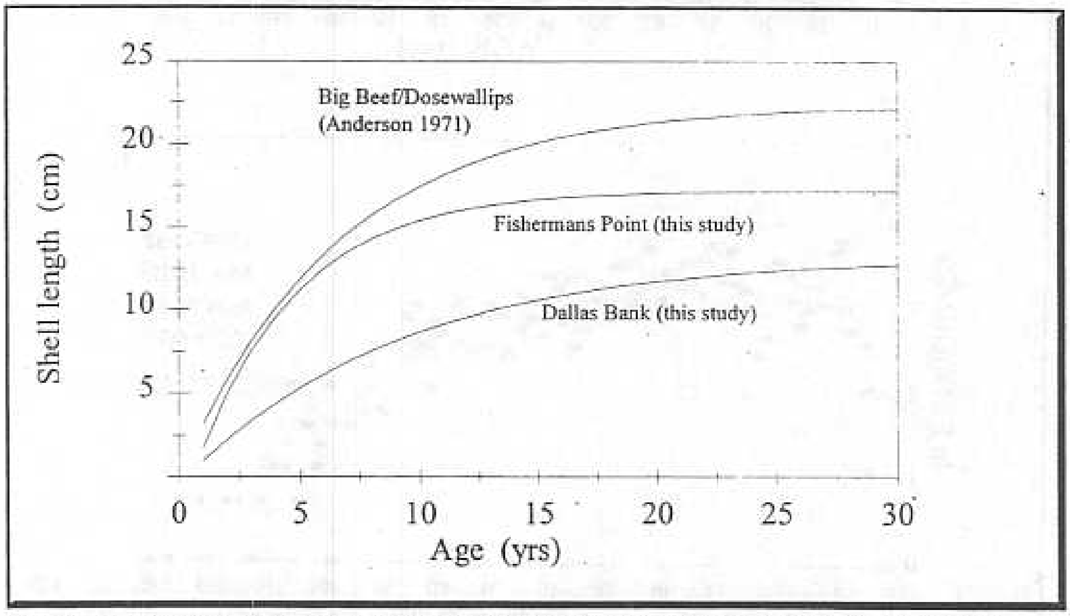


Figure 12. The von Bertalanffy growth curves for geoduck growth at the fastest growth site (Fishermans Pt.) and the slowest growth site (Dallas Bank) in this study.

Length-weight Relationship

Goodwin (1976) calculated an allometric length-weight relationship for Washington geoducks in log-log form. We converted this to the more familiar power curve form $w_a = xL_a^y$, where w_a = weight (in g) at age a, L_a = shell length (in cm) at age a (Table 4).

Sex Ratio

The proportion of males (p_m) in the geoduck population was set to $p_m = 0.5$ based on a 50:50 sex ratio for geoducks older than 10 years (Goodwin and Pease 1989).

Maturity

The proportion of sexually mature geoducks at age was estimated by fitting a simple logistic curve to maturity data from published sources. Anderson (1971) found that 50% of his sample of geoducks was mature at 75 mm and an age that he estimated to be 3 years. The Washington growth curves described above suggest that this length would be attained in roughly 5 years, depending on the site. Sloan and Robinson (1984) reported that geoducks mature at 5 years and reproduce for at least a 100-year period with no "reproductive senility." They stated that "unequivocally mature geoducks" were 6 to 103 years old (late-active males) and 12 to 95 years old (late-active females). Based on these two sources, we fit a logistic curve with the least squares method and two data points, whereby 50% of the female geoducks would mature at 5 years and 100% by 12 years. The proportion of mature geoducks (Φ) at age a is described by

$$\Phi_a = 1/(1 + \exp^{xa+y}) \tag{17}$$

where a is age in years, $x = -1.9$, and $y = 9.5$.

Fishery Selectivity

Fishery selectivity at age was based loosely on Harbo *et al.* (1983), who reported that recruitment to the British Columbia geoduck fishery begins at 4 years and is complete by 12 years. We fit a simple logistic curve using the least squares method and two data points, assuming geoducks enter the fishery at roughly 4 years and, to more conservatively model fishery selectivity, assume that geoducks are fully selected by 8 years.

$$v_a = 1/(1 + \exp^{xa+y}) \tag{18}$$

where v_a is the proportion of geoducks of age a selected by the fishery, a is age in years, $x = -1.5$, and $y = 8$.

Stock-recruit Relationship

Nothing is known about the form or steepness of the stock-recruit (S-R) relationship for geoducks. We therefore set the Beverton-Holt shape parameter (A) equal to 1.0 for all model runs. In other words, we assumed that recruitment was independent of spawning stock abundance. This assumption is reviewed below in *Discussion*.

Maximum Age

As a practical convenience, the equilibrium yield model uses an "accumulater age" category (a_{max}) as the final age category, encompassing all ages $a \geq a_{max}$. For this study, we set $a_{max} = 25$, which implicity assumes that there are no significant changes in growth, selectivity, or maturity beyond age 24. This assumption is reasonable for geoducks, which reach asymptotic size between the ages of 10-20 years (Hoffmann *et al.* 1999).

Results

Fishing Mortality Rates for Five Harvest Strategies

We ran the model for each site, varying only the growth parameters based on the analysis of growth presented in Hoffmann *et al.* (1999). The only sites where growth parameter estimates (specifically, the growth constant k) could be pooled were five of the six Hood Canal sites. In all other cases, site-specific growth parameters could not be pooled, and therefore separate model outputs were calculated for each site. All inputs except growth parameters were identical for each model run (Table 1). Growth parameters used as site-specific input are shown in Table 5.

Table 5. Bench mark instantaneous fishing mortality rates for fully-selected geoducks ($v_a = 1.0$) from seven sites in Washington. Model inputs except growth parameters are from Table 4. Growth parameter estimates are from Hoffmann *et al.* (1999).

Region	Site	n (sites)	L_∞ (cm)	k	t_0	F_{max}	$F_{0.1}$	$F_{35\%}$	$F_{40\%}$	$F_{50\%}$
South Sound	Hunter Point	1	16.4	0.23	0.72	0.090	0.036	0.036	0.029	0.020
	Herron Island	1	13.2	0.15	0.42	0.064	0.031	0.032	0.027	0.018
Central Sound	Agate Passage	1	15.8	0.20	0.18	0.085	0.035	0.035	0.029	0.020
	Blake Island	1	14.6	0.16	0.81	0.064	0.031	0.032	0.027	0.019
Hood Canal	Five sites pooled	5	12.8	0.16	0.47	0.067	0.032	0.033	0.027	0.019
	Fishermans Point	1	16.8	0.24	0.55	0.100	0.037	0.036	0.030	0.020
Strait	Dallas Bank	1	12.0	0.11	0.33	0.053	0.028	0.030	0.025	0.018

Values of the instantaneous fishing mortality rate (F) for five commonly-used constant harvest rate strategies are shown in Table 5. F_{max} is the fishing mortality rate that produces, over the long run, the maximum yield per recruit (YPR). $F_{0.1}$ is a common alternative to F_{max}, and is the rate of fishing mortality at which the marginal YPR is 10% of the marginal YPR for a lightly exploited fishery (Deriso 1987). $F_{35\%}$, $F_{40\%}$ and $F_{50\%}$ are spawning biomass per recruit (SPR) based harvest rates which reduce SPR to either 35%, 40% or 50% of the unfished level (Clark 1991).

F_{max} ranged from 0.053 to 0.100 depending on the site (Table 5). These rates correspond to annual harvest rates (μ) of 5.1 - 9.4% of the exploitable geoduck biomass. The Strait of Juan de Fuca region, represented by the single sampling site at Dallas Bank, produced the lowest value, while Fishermans Point in Hood Canal produced the highest value. The F_{max} strategy reduced SPR to 15-21% of the unfished level, depending on the site. Values for $F_{0.1}$ ranged from 0.028 to 0.037, corresponding to annual harvest rates of 2.7 - 3.6%. This strategy reduced SPR to 35-37% of the unfished level, depending on the site.

Values for $F_{35\%}$ were, predictably, nearly identical to the $F_{0.1}$ rates, ranging from 0.30 - 0.36 (μ = 2.9 - 3.5%). F values for the $F_{40\%}$ strategy ranged from 0.025 - 0.030 (μ = 2.4 - 2.8%). The mean F value for the $F_{40\%}$ strategy was 0.028, corresponding to μ = 2.7%. F values for the $F_{50\%}$ strategy ranged from 0.018 - 0.020 (μ = 1.8 - 2.0%).

Model Sensitivity to Parameter Estimates

All the parameter estimates used to drive the model are subject to varying degrees of uncertainty. It is therefore reasonable to ask what might happen to our predictions if the true values of M or k, for example, were much lower or higher than our estimates. We tested the sensitivity of the model by running it with a range of values for each parameter in turn, while holding all other parameters constant. Values ranging from one-tenth the "best" parameter estimate (from Tables 4 and 5) to three times the estimated value were used in the analysis. Only the fishing mortality rates corresponding to the $F_{40\%}$ strategy were calculated, but the trend for other strategies would be similar.

The model was most sensitive to the estimate of M, with $F_{40\%}$ values ranging from 0.003 to 0.068 as M was increased from one tenth to three times our "best" estimate of M = 0.0226 (Figure 13). The model was far less sensitive to the other parameter estimates, as evidenced by the relatively flat $F_{40\%}$ trajectories for values of the growth coefficient k, the selectivity constant y, and the maturity constant y. For example, varying the value of k from one-tenth to three times our "best" estimate resulted in $F_{40\%}$ values which ranged only from 0.021 to 0.033.

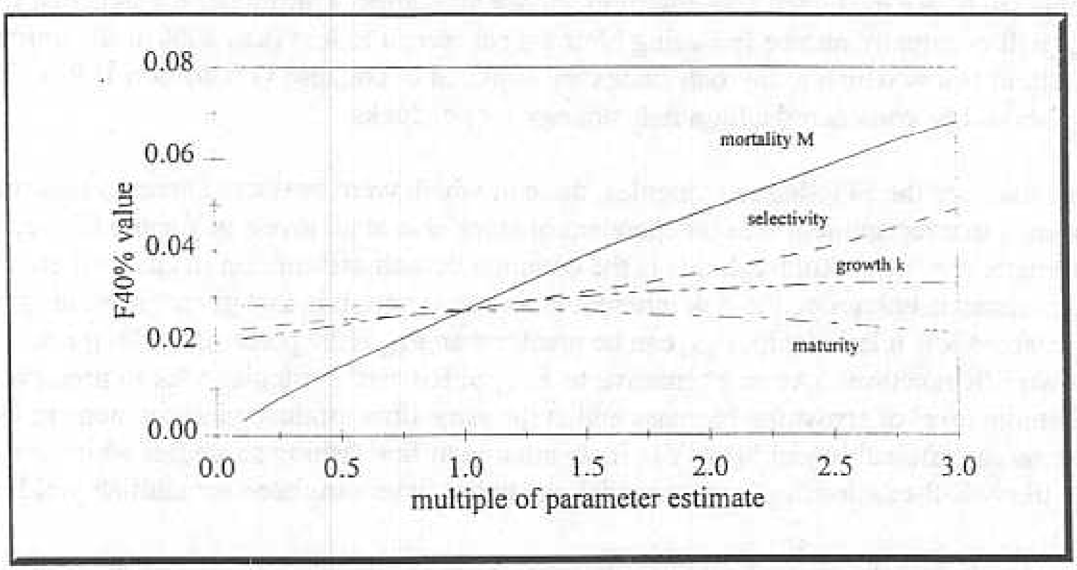


Figure 13. The effect of different parameter estimates on model-derived F $_{40\%}$ values.

Discussion

Our primary objective in equilibrium modeling was to simulate the long-term results of various geoduck fishing strategies, both in terms of yield and spawning biomass per recruit. Before discussing our results, it is perhaps necessary to explain why we attach such importance to geoduck harvest rate strategies, particularly since the differences between many of the modeled options may appear trivial.

In many fisheries, especially those in which biomass is small or estimated with great uncertainty, debating a 1% difference between annual harvest rate options would indeed be trivial. But in Washington's geoduck fishery, where the exploitable biomass is large (73,843 t in 1999; Sizemore and Ulrich 1999) and the price is high, even tiny incremental differences in the recommended harvest rate have tremendous economic significance. Moreover, because geoducks have a low M (and presumably a low intrinsic rate of increase), small differences in annual harvest rates can have profound cumulative effects on stock size, especially if the harvest rate is set too high. This is not to discount the importance of good biomass estimates, but we believe there are several reasons why Washington managers should place the greatest emphasis on improved harvest rate strategies rather than improved biomass estimates. First, biomass estimates for individual geoduck beds in Washington have coefficients of variation (CV) averaging about 20%. Simulation tests suggest that biomass estimation errors of this magnitude are unlikely to result in substantial degradation of long-term harvest performance (Frederick and Peterman 1995). Second, even greatly increased sampling is not likely to improve biomass estimate CVs very much. Third and most importantly, errors in biomass estimation are assumed to be reasonably unbiased. An error in setting the annual harvest rate, on the other hand, will have a persistent and cumulative effect on stocks in only one direction, either underharvest or overharvest. We therefore believe that, given reasonable estimates of stock size, choosing a harvest strategy remains the most critical aspect of geoduck management.

In this study, we evaluated five common harvest strategies. Our model predicts that fishing at F_{max} will eventually reduce spawning biomass per recruit to less than 20% of the unfished level, a threshold below which many fish stocks are assumed to collapse (Thompson 1993). Therefore, F_{max} should be considered a high risk strategy for geoducks.

Less risky are the SPR-based strategies, three of which were evaluated here. In this study, we assumed that recruitment was independent of stock size at all levels of fishing (Beverton-Holt parameter $A = 1.0$). Although this is the common default assumption in cases where the S-R relationship is unknown, the risk inherent in this assumption is that given an existing but undetected S/R relationship, $F_{x\%}$ can be greater than F_{MSY} (the preferred fishing rate with a known S/R function). As an alternative to F_{max}, SPR-based strategies seek to preserve some minimum level of spawning biomass and at the same time produce yields which are close to the maximum sustainable yield (MSY). In an attempt to find fishing strategies which are robust for any likely S-R relationship, recent modeling studies have simulated groundfish yields using a range of typical life history parameters and realistic S-R models. Clark (1991) showed that fishing at $F_{35\%}$ would achieve at least 75% of MSY for a wide range of deterministic S-R relationships. On the basis of his results, $F_{35\%}$ has been adopted as a target rate for a number of fish stocks in Alaska and the U.S. Pacific coast. Clark (1993) later revised his recommendation to $F_{40\%}$ after considering variability in recruitment, but remarked that "it would be silly to argue very hard for or against any specific rate between $F_{35\%}$ and $F_{45\%}$." Mace (1994) also recommended $F_{40\%}$, which she claimed was a modest improvement over $F_{35\%}$. She states that $F_{40\%}$ represents a risk-averse fishing strategy in the common situation where there is adequate information to place bounds on all relevant life history parameters except the S-R relationship. Quinn and Szarzi (1993) modeled clam fisheries in Alaska and recommended SPR-based strategies equivalent to a range of $F_{30\%}$ to $F_{45\%}$.

On the basis of the results presented here, state and Tribal geoduck managers formally agreed on December 5, 1997 to an $F_{40\%}$ strategy for geoducks, applying an instantaneous fishing mortality rate of $F = 0.028$; the corresponding annual harvest rate for fully selected age classes (μ) is 0.027, or 2.7% of the exploitable biomass (*Appendix A* to state/Tribal geoduck agreements). Annual fishing quotas within each of the six management regions are calculated as the product of this harvest rate and the estimated exploitable biomass within the region (available from dive survey data). British Columbia managers calculate annual quotas using a fixed harvest rate of 1% (Campbell *et al.* 1998), but until recently this rate was applied to the estimated *virgin* biomass rather than current biomass estimates as is done in Washington.

Suggestions for Future Research

A secondary objective of our study was to determine which of the estimated geoduck life history parameters were most influential in predictions of yield and spawning biomass per recruit. The model was most sensitive to the estimate of natural mortality (M), while growth, selectivity, and maturity parameters had relatively little effect on SPR-based fishing mortality rates. This suggests that future research monies are best spent making more reliable estimates of M.

Our estimate of $M = 0.0226$ is similar to estimates from British Columbia. Sloan and Robinson (1984) estimated $M = 0.035$ at a single site, while Breen and Shields (1983) reported $M = 0.01$ to 0.04 in five populations. Noakes (1992) estimated $M = 0.03$ to 0.04 at three sites. Both our estimate and the British Columbia estimates relied on the catch curve method, which assumes that mortality rate is uniform with age and that recruitment has been constant over the range of age-groups analyzed. There is some suggestion in our age-frequency data that a shift in geoduck recruitment has occurred which could have biased the estimate of M. Age frequencies did not begin to decline until about age 25, a pattern in catch curves which is often due to inefficient sampling of younger age classes. But for geoducks, which grow quickly and are fully selected by the commercial fishery at half this age (Harbo *et al.* 1983), sampling inefficiency is not a plausible explanation for the low numbers of geoducks in the 10-25 year age group. Instead, low numbers of 10 - 25 year-old geoducks may indicate poor recruitment during the 15-year period prior to sampling. This suggests that recruitment declined during the period 1955-1970 (prior to the advent of a fishery), and perhaps more recently. Sloan and Robinson (1984) suggested the possibility of a similar decline in recruitment during the same time period in British Columbia.

Thus, catch curve estimates of M for geoducks based on older age classes may not accurately represent current trends in natural mortality. They likewise reveal nothing about M for younger geoducks. In either case, our results indicate that biases in the estimate of M will have a major influence on model-based predictions of yield and spawning biomass per recruit. Independent estimates of M should therefore be a high priority for research.

Given the fact that geoducks are entirely sedentary, direct estimates of M for adult geoducks are possible using non-invasive tags. In 1998 WDFW began testing a tagging method for estimating M at a previously unfished site in northern Hood Canal. Divers "tagged" 1,128 adult geoducks (>3-4 yrs) in May 1998 by placing thin plastic stakes next to geoduck siphons at a distance of 3 inches. Geoducks were tagged within 3 ft of three lines running offshore and anchored in depths of -18 m to -70 ft MLLW. One year later, we found 875 of the original 1,128 tags remaining in the substrate. Over a 6-day period, siphons were visible next to 856 of the tags. We used a venturi dredge to excavate the 19 tags with no visible siphons; 4 of these geoducks were alive, 14 were dead, and one tag had no sign of a living or dead geoduck. The annual survival rate (S) for all three lines was estimated as $N_1 / N_0 = 861/875 = 0.984\ y^{-1}$ (95% CI = 0.991 - 0.973) and the corresponding estimate of M was 0.016 y^{-1}. Estimates of S on individual lines ranged from 0.996 to 0.0.970, suggesting that survival and mortality rates vary widely even over small spatial scales. The direct estimate of M makes fewer assumptions than catch curve estimates and is less expensive. Now that the tagging method has proved feasible, experiments to estimate M at sites throughout Washington are recommended.

Although the model was not nearly as sensitive to growth parameter estimates as it was to M, Hoffmann *et al.* (1999) found evidence for site-specific differences in the growth parameter k which were of "managerial significance" (i.e., of a magnitude to influence model-derived target fishing mortality rates). However, since the growth sample sites were not selected at random, regional estimates of k which are simply averages of the estimated site k's will be biased. One solution, albeit a costly one, is to collect additional growth samples from a number of randomly-selected sites in all regions. Another possible solution is to analyze the empirical relationship between mean shell length at sites and the site-specific estimate of k; preliminary studies suggest that there is a positive linear relationship between the two. If this relationship proves significant, the huge volume of existing shell length data gathered every year since 1968 during pre-fishing surveys could be parsed by management region to obtain regional estimates of mean shell length. These could then be compared statistically and used to calculate empirical estimates of k for each region. This approach, if feasible, would not require any additional field work, but would instead rely on the large and already-existing morphological database for geoducks.

Finally, we plan to continue the empirical "recovery" study on at least 15 previously fished geoduck beds. This study tracks changes in geoduck density before fishing, immediately after fishing, and then at intervals following fishing. A recovery rate for each tract is estimated from the difference in density between the first post-harvest survey and the second post-harvest survey. The study is expected to provide empirical estimates of the time required for geoduck density to return to pre-fishing levels. Thus far, three surveys have been completed at all the sites: a survey prior to fishing, a survey immediately after harvest, and a second post-harvest survey. The decrease in geoduck density immediately after fishing averaged 72% and ranged from a low of 19% to a high of 95%. The elapsed time between the first and second post-harvest surveys ranged from 4 to 11 years, averaging 8 years. During this period following fishing, density increased on all the tracts. The average estimated time to recover to pre-fishing density (assuming 100% removal of all geoducks and linear recovery) was 39 years, ranging from a low of 11 years to a high of 73 years. Thus, the proportion of fished biomass replaced each year on average was 1/39 = 0.0256. A simple biomass dynamics model was used to compare the average recovery time estimated thus far (39 years) with the existing annual harvest rate of 2.7%. The model predicted that a recovery time of 39 years and fishing at 2.7% every year eventually reduced biomass to 49% of its unfished level. Since this is greater than the 40% target level for the $F_{40\%}$ strategy, the current harvest rate of 2.7% is considered conservative. However, the study must be continued at intervals to better define the shape of the recovery curve and the time required for recovery.

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Appendix 1
Geoduck Survey Data Sheets

✓ PREFISHING
__ POST FISHING
__ OTHER____

DIG __

REFERENCE: 99207

GEODUCK TRANSECT (900 ft.²) DATA SHEET

LOCATION: PILOT POINT REGION CODE CS TRACT CODE 06200

STATION: 87 DATE: 4/28/99 Chart Datum NAD 27

START TIME: 1041 DEPTH CORRECTION: {+1.6}

DGPS POSITION: LATITUDE: 4752962 LONGITUDE: 12230611

UNCORRECTED BEG. DEPTH: 48 ft. CORRECTED BEG. DEPTH: 46 ft.

UNCORRECTED END DEPTH: 26 ft. CORRECTED END DEPTH: 24 ft.

GEODUCK COUNT 1: 7 GEODUCK COUNT 2: 20

SHOW FACTOR: 0.75

ADULT CUCS: 4 JUVENILE CUCS: 0

SUBSTRATE RATING: Mud 1 Sand 2 Peagravel___ Gravel___ Shell___ Cobble___

Boulder___ Unstable_____ Other wood debris

P1: 6 P2: 7 P3:__ P4:__ P5:__ P6:__ P7:__ P8:__ P9:__ P10:__ P11:__ P12:__

A1: 1 A2: 18 A3: 26 A4: 28 A5: 29 A6: 4 A7:__ A8:__ A9:__ A10:__ A11:__ A12:__

A13:__ A14:__ A15:__ OTHER:____

DIVER NAME(s) AB BS BOTTOM TIME 36 min.

FROM BUOY # 36 TRANSECT LINE 82 → 87

COMPASS COURSE 270° MAGNETIC

ADDITIONAL COMMENTS:

END @: 1117

DGPS 47°52971'

122°30641'

Enter ☑ E.C. ☑

GEODUCK WATER-JET HARVEST DATA

REFERENCE: 99052

REGION: CS TRACT CODE: 06200 STATION: 52 DATE: 4/21/99

START TIME: 1048 DEPTH CORRECTION: +8.2

DGPS POSITION: LATITUDE: 4753083 LONGITUDE: 12230646

UNCORRECTED BEG. DEPTH: 56 ft. CORRECTED BEG. DEPTH: 48 ft.

UNCORRECTED END DEPTH: 57 ft. CORRECTED END DEPTH: 49 ft.

SUBSTRATE RATING: Mud 1 Sand 1 Peagravel___ Gravel___ Shell___ Cobble___

Boulder___ Other:___

DIFFICULTY: 1 ABUNDANCE: 2 DEPTH: 1 COMPACT: 0 GRAVEL: 0 SHELL: 1

TURBIDITY: 0 ALGAE: 0 COMMERCIAL: Y NUMBER DUG: 10

NO GUT SHOT!

TIME TAKEN TO DIG GEODUCKS: 5 (minutes) NUMBER GEODUCK > 907 (g) 6

DIVER NAME(s) AB BOTTOM TIME 14 min.

VALVE LENGTH[1] (mm)	WHOLE WEIGHT (g)	SIPHON WEIGHT (g)	GS[2]	BV[3]	COMMERCIAL QUALITY (y/n)	COMMENTS
1. 136	1035	205				
2. 125	1027	270				
3. 137	1135	294				
4. 123	656	169				
5. 122	857	229				
6. 167 LV	1170	269				
7. 106 LV	345	107		✓RV		WATER LOSS
8. 137	1015	242				
9. 125	495	103				
10. 155	1051	191				
11.						
12.						
13.						

[1]LENGTH = RIGHT VALVE WHEN NOT BROKEN
[2]GS = GUT SHOT (WATER LOSS)
[3]BV=BROKEN VALVE

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Enter ☑ E.C. ☑

Appendix 2
Geoduck Data Sheet Codes

Geoduck Survey Animals List - number organized Last updated: 11/10/99

	Taxonomer	Common Name	Group	Phylum
0	*Elzippo nullus*	NO ANIMALS	ENTROPY	KARMA
1	*Butter, littleneck, venus'*	HARDSHELL CLAM	BIVALVE	MOLLUSC
2	*Tresus spp.*	HORSE CLAM	BIVALVE	MOLLUSC
3	*Ptilosarcus gurneyi*	SEA PEN	MISC.	COELENTERATE
4	*Parastichopus californicus*	SEA CUCUMBER	CUCUMBER	ECHINODERM
5	*Unspecified*	GHOST SHRIMP	SHRIMP	ARTHROPOD
6	*Cancer magister*	DUNGENESS CRAB	CRAB	ARTHROPOD
7	*Cancer productus*	RED ROCK CRAB	CRAB	ARTHROPOD
8	*Cancer gracilis*	GRACEFUL CRAB	CRAB	ARTHROPOD
9	*Strongylocentrotus*	SEA URCHIN	URCHIN	ECHINODERM
10	*Mya truncata*	TRUNCATED MYA	BIVALVE	MOLLUSC
11	*Unspecified Pectinid*	SCALLOP	BIVALVE	MOLLUSC
12	*Chaetopterid polychaete tubes*	ROOTS	MISC.	ANNELID
13	*Unspecified Pholadid*	PIDDOCK	BIVALVE	MOLLUSC
14	*Panomya beringiana*	FALSE GEODUCK	BIVALVE	MOLLUSC
15	*Unspecified*	ANEMONE	ANEMONE	CNIDARIA
16	*Polinices lewisi*	MOON SNAIL	GASTROPOD	MOLLUSC
17	*Stylatula elongata*	SEA WHIP	MISC.	COELENTERATE
18	*Pycnopodia helianthoides*	SUNFLOWER STAR	SEA STAR	ECHINODERM
19	*Unspecified*	NUDIBRANCH	MISC.	MOLLUSC
20	*Unspecified*	HERMIT CRAB	CRAB	ARTHROPOD
21	*Luidia foliolata*	SAND STAR	SEA STAR	ECHINODERM
22	*Pisaster brevispinus*	SHORT-SPINED STAR	SEA STAR	ECHINODERM
23	*Evasterias troschelii*	FALSE OCHRE STAR	SEA STAR	ECHINODERM
24	*Loligo opalescens*	SQUID EGGS	CEPHALOPOD	MOLLUSC
25	*Polinices lewisii*	MOON SNAIL EGGS	GASTROPOD	MOLLUSC
26	*Unspecified*	FLATFISH	FISH	CHORDATE
27	*Dendraster excentricus*	SAND DOLLAR	SEA BISCUIT	ECHINODERM
28	*Modiolus rectus*	HORSE MUSSEL	BIVALVE	MOLLUSC
29	*Henricia leviuscula*	BLOOD STAR	SEA STAR	ECHINODERM
30	*Unspecified Raja*	SKATE	FISH	CHORDATE
31	*Pachycerianthus fimbriatus*	BURROWING ANEMONE	ANEMONE	CNIDARIA
32	*Metridium senile*	PLUMED ANEMONE	ANEMONE	CNIDARIA
33	*Dermasterias imbricata*	LEATHER STAR	SEA STAR	ECHINODERM
34	*Hydrolagus colliei*	RATFISH	FISH	CHORDATE
35	*Unspecified cottid*	SCULPIN	FISH	CHORDATE
36	*Unspecified*	BURROWING CUCUMBER	CUCUMBER	ECHINODERM
37	*Nassarius spp.*	BASKET SNAIL	GASTROPOD	MOLLUSC
38	*Anarrhichthys ocellatus*	WOLF EEL	FISH	CHORDATE
39	*Unspecified*	STARFISH	SEA STAR	ECHINODERM
40	*Sebastes spp.*	COLORED ROCKFISH	FISH	CHORDATE
41	*Sebastes melanops*	BLACK ROCKFISH	FISH	CHORDATE
42	*Hexagrammos sp.*	GREENLING	FISH	CHORDATE
43	*Ophiodon elongatus*	LINGCOD	FISH	CHORDATE
44	*S. fransiscanus*	RED URCHIN	URCHIN	ECHINODERM
45	*S. purpuratus*	PURPLE URCHIN	URCHIN	ECHINODERM
46	*S. droebachiensis*	GREEN URCHIN	URCHIN	ECHINODERM
47	*Anthopleura xanthogrammica*	LARGE GREEN ANEMONE	ANEMONE	CNIDARIA
48	*Unspecified*	MYSIDS	MISC.	ARTHROPOD
49	*Pisaster ochraceus*	OCHRE STAR	SEA STAR	ECHINODERM
50	*Scorpaenichthys marmoratus*	CABEZON	FISH	CHORDATE
51	*Crassadoma gigantea*	ROCK SCALLOP	BIVALVE	MOLLUSC
52	*Eschrictious robustus*	GREY WHALE	MAMMAL	CHORDATE
53	*Haliotis kamtschatkana*	ABALONE	GASTROPOD	MOLLUSC
54	*Ammodytes hexapterus*	SAND LANCE	FISH	CHORDATE
55	*Unspecified embiotocid*	PERCH	FISH	CHORDATE
56	*Solaster spp.*	SUN STAR	SEA STAR	ECHINODERM
57	*Octopus spp.*	OCTOPUS	MISC.	MOLLUSC
58	*Balanus nubilis*	GIANT BARNACLE	MISC.	ARTHROPOD
59	*Cryptochiton stelleri*	GUMBOOT CHITON	MISC.	MOLLUSC
60	*Chlamys rubida,C. hastata.*	SINGING SCALLOPS	BIVALVE	MOLLUSC
61	*Fusitriton oregonensis*	OREGON TRITON	GASTROPOD	MOLLUSC
62	*Unspecified*	GOBIE	FISH	CHORDATE

63	*Orcus orcinus*	KILLER WHALE	MAMMAL	CHORDATE
64	*Panopea abrupta*	GEODUCK	BIVALVE	MOLLUSC
65	*Telmessus cheiragonus*	HELMET CRAB	CRAB	ARTHROPOD
66	*Squalus acanthias*	DOGFISH SHARK	FISH	CHORDATE
67	*Mytilus californianus*	CALIFORNIA MUSSEL	BIVALVE	MOLLUSC
68	*Stylasterias forreri*	FISH-EATING STAR	SEA STAR	ECHINODERM
69	*Clupea harengus pallasi*	HERRING	FISH	CHORDATE
70	*Syngnathus leptorhynchus*	PIPEFISH	FISH	CHORDATE
71	*Unspecified serpulid*	TUBE WORM	MISC.	ANNELID
72	*Raja spp.*	SKATE EGGS	FISH EGGS	CHORDATE
73	*Unspecified*	ASSORTED SHRIMP	SHRIMP	ARTHROPOD
74	*Clinocardium nuttalli*	COCKLE	BIVALVE	MOLLUSC
75	*Unspecified agonid*	POACHER	FISH	CHORDATE
76	*Poraniopsis inflata*	SPINY STAR	SEA STAR	ECHINODERM
77	*Crossaster papposus*	ROSE STAR	SEA STAR	ECHINODERM
78	*Mediaster aequalis*	VERMILLION STAR	SEA STAR	ECHINODERM
79	*Oncorhynchus spp.*	SALMON	FISH	CHORDATE
80	*Gadus macrocephalus*	PACIFIC COD	FISH	CHORDATE
81	*Cucumaria miniata*	ORANGE CUCUMBER	CUCUMBER	ECHINODERM
82	*Eupentacta quinquesemita*	WHITE CUCUMBER	CUCUMBER	ECHINODERM
83	*Urticina sp.*	STRIPED ANEMONE	ANEMONE	CNIDARIA
84	*Unspecified holothurian*	BLACK CUCUMBER	CUCUMBER	ECHINODERM
85	*Gorgonocephalus euchemis*	BASKET STAR	SEA STAR	ECHINODERM
86	*Orthasterias koehleri*	RAINBOW STAR	SEA STAR	ECHINODERM
87	*Lopholithodes mandti*	BOX CRAB	CRAB	ARTHROPOD
88	*Unspecified Porifera*	LARGE SPONGES	MISC.	PORIFERA
89	*Diadora spera*	KEYHOLE LIMPET	GASTROPOD	MOLLUSC
90	*Patira miniata*	BAT STAR	SEA STAR	ECHINODERM
91	*Unspecified*	CORAL	MISC.	COELENTERATE
92	*Pteraster tesselatus*	ORANGE PEEL STAR	SEA STAR	ECHINODERM
93	*Aulorhynchus flavidus*	TUBESNOUT	FISH	CHORDATE
94	*Pododesmus cepio*	JINGLESHELL OYSTER	BIVALVE	MOLLUSC
95	*Pteraster tesselatus*	SLIME STAR	SEA STAR	ECHINODERM
96	*Hydrolagus colliei*	RATFISH EGG CASE	FISH	CHORDATE
97	*Ophiopholis aculeata*	BRITTLE STAR	SEA STAR	ECHINODERM
98	*Diopatra ornata*	DECORATING TUBEWORM	MISC	ANNELID
99	*Pugettia spp.*	DECORATOR CRAB	CRAB	ARTHROPOD
100	*Unspecified arthropod*	ARTHROPOD	MISC.	ARTHROPOD
101	*Unspecified fish*	FISH	FISH	CHORDATE
102	*Unspecified cnidarian*	CNIDARIA	MISC.	CNIDARIA
103	*Unspecified echinoderm*	ECHINODERM	MISC.	ECHINODERM
104	*Unspecified mollusc*	MOLLUSC	BIVALVE	MOLLUSC
105	*Unspecified worm*	WORM	MISC.	ANNELID
106	*Unspecified marine mammal*	MARINE MAMMAL	MAMMAL	CHORDATE
107	*Unspecified fish eggs*	FISH EGGS	FISH EGGS	CHORDATE
108	*Composmyax subdiaphana*	MILKY PACIFIC VENUS	BIVALVE	MOLLUSC
109	*Glycymeris subobsoleta*	BITTERSWEET ARKSHELL	BIVALVE	MOLLUSC
110	*Humilaria kennerleyi*	KENNERLY'S VENUS	BIVALVE	MOLLUSC
111	*Oregonia gracilis*	DECORATOR CRAB	CRAB	ARTHROPOD
112	*Terebellid sp.*	TEREBELLID TUBE WORM	MISC.	ANNELID
113	*Solen sicarius*	JACK KNIFE CLAM	BIVALVE	MOLLUSC
114	*Semele rubropicta*	ROSE SEMELE	BIVALVE	MOLLUSC
115	*Opisthobranch sp.*	OPISTHOBRANCH	MISC.	MOLLUSC
116	*Sabellid sp.*	SABELLID TUBE WORM	MISC.	ANNELID
117	*Hippasteria spinosa*	SPINY STAR	SEA STAR	ECHINODERM
118	*Pentomera populifera*	MUD CUCUMBER	SEA CUCUMBER	ECHINODERM
119	*Chlamys rubida*	PINK SCALLOP	BIVALVE	MOLLUSC
120	*Chlamys hastata*	SPINY SCALLOP	BIVALVE	MOLLUSC
121	*Leptasterias hexactis*	SIX-RAYED SEA STAR	SEA STAR	ECHINODERM
122	*Patinopecten caurinus*	WEATHERVANE SCALLOP	BIVALVE	MOLLUSC
123	*Scyra acutifrons*	SHARP-NOSED CRAB	CRAB	MOLLUSC
124	*Munida quadrispina*	PINCH BUG	CRAB	MOLLUSC
125	*Sebastes caurinus*	COPPER ROCKFISH	FISH	CHORDATE
126	*Sebastes maliger*	QUILLBACK ROCKFISH	FISH	CHORDATE
127	*Sebastes auriculatus*	BROWN ROCKFISH	FISH	CHORDATE

128	*Platichthys stellatus*	STARRY FLOUNDER	FISH	CHORDATE
129	*Parophrys vetulus*	ENGLISH SOLE	FISH	CHORDATE
130	*Lepidopsetta bilineata*	ROCK SOLE	FISH	CHORDATE
131	*Pleuronichthys coenosus*	C-O SOLE	FISH	CHORDATE
132	*Psettichthys melonostictus*	SAND SOLE	FISH	CHORDATE
133	*Citharichthys sp.*	SANDDAB	FISH	CHORDATE
134	*Cribrinopsis fernaldi*	CRIMSON ANEMONE	ANEMONE	CNIDARIA
135	*Unspecified tunicate*	SESSILE TUNICATES	MISC.	ASCIDIAN
136	*Unspecified bryozoan*	MOSS ANIMAL	MISC.	BRYOZOAN
137	*Unspecified flatworm*	FLATWORM	MISC.	PLATYHELMINTHES
138	*Unspecified peanut worm*	PEANUT WORM	MISC.	SIPUNCULID

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Geoduck Survey Plants List Last updated: 11/10/99

CODE	TAXONOMER	DESCRIPTION	GROUP	COLOR
0	*Elzippo nullus*	NO PLANTS		ENTROPY
1	*Laminaria and similar species*	LAMINARIA	Laminaria	BROWN ALGAE
2	*Nereocystis luetkeana*	BLADDER KELP	Laminaria	BROWN ALGAE
3	*Ulva spp.*	SEA LETTUCE		GREEN ALGAE
4	*Zostera marina*	EEL GRASS		ANGIOSPERM
5		SMALL MIXED ALGAE	red-brown-green	ALGAE
6	*Unspecified*	SMALL RED ALGAE		RED ALGAE
7	*Unspecified*	LARGE RED ALGAE		RED ALGAE
8	*Diatoms*	BROWN SLIME		YELLOW-BROWN ALGAE
9	*Unspecified*	SMALL GREEN ALGAE		GREEN ALGAE
10	*Unspecified*	SMALL BROWN ALGAE		BROWN ALGAE
11	*Pterygophora californica*	FEATHER PALM ALGAE	Laminaria	BROWN ALGAE
12	*Macrocystis integrifolia*	CALIFORNIA KELP	Laminaria	BROWN ALGAE
13	*Unspecified*	LARGE BROWN ALGAE		BROWN ALGAE
14	*Unspecified*	FILAMENTOUS BROWN ALGAE		BROWN ALGAE
15	*Unspecified*	FLUFFY BROWN ALGAE		BROWN ALGAE
16	*Unspecified*	FILAMENTOUS GREEN ALGAE		BROWN ALGAE
17	*Unspecified*	FILAMENTOUS GREEN ALGAE		GREEN ALGAE
18	*Corallina, Bosiella*	ARTICULATED CORALLINE ALGAE	Corrallinaceae	RED ALGAE
19	*Agarum spp.*	AGARUM	Laminaria	BROWN ALGAE
20	*Costaria costada*	COSTARIA	Laminaria	BROWN ALGAE
21	*Alaria nana*	ALARIA	Laminaria	BROWN ALGAE
22	*Pleurophycus gardneri*	PLEUROPHYCUS	Laminaria	BROWN ALGAE
23	*Desmarestia spp*	DESMARESTIA	Desmarestiales	BROWN ALGAE
24	*Gigartina papillata*	GIGARTINA	Gigartinales	RED ALGAE
25	*Porphyra spp.*	PORPHYRA	Bangiales	RED ALGAE
26	*Lithothamnion, Lithophyllum*	CRUSTOSE CORALLINE ALAGE	Corrallinaceae	RED ALGAE
27	*Opuntiella californica*	OPUNTIELLA	Gigartinales	RED ALGAE
28	*Gracilaria verrucosa*	GRACILARIA	Gigartinales	RED ALGAE
29	*Sarcodiotheca gaudichaudi*	SARCODIOTHECA	Gigartinales	RED ALGAE
30	*Polyneura spp.*	POLYNEURA	Ceramiales	RED ALGAE
31	*Enteromorpha intestinalis*	ENTEROMORPHA	Cladophorales	GREEN ALGAE
32	*Phyllospadix scouleri*	PHYLLOSPADIX	Surf Grass	ANGIOSPERM
33	*Egregia menziesi*	EGREGIA	Laminaria	BROWN ALGAE
34	*Fucus distichus edentatus*	FUCUS	Fucales	BROWN ALGAE
35	*Iridea cordata*	IRIDEA	Gigartinales	RED ALGAE
36	*Ceramium spp.*	CERAMIUM	Ceramiales	RED ALGAE

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YIELD ESTIMATE FOR HORSE CLAMS IN WASHINGTON STATE

Prepared by Alex Bradbury
Washington Department of Fish and Wildlife
June 6, 1996

INTRODUCTION

Two species of horse or "gaper" clams *(Tresus nuttallii and T. capax)* exist in Washington waters. The two species often coexist from the low intertidal to subtidal depths of at least 150 feet, although *T nuttallii* is more abundant subtidally than *T. capax (Campbell et al.* 1990). The two species cannot be reliably distinguished while still in the substrate. Thus, from a practical fisheries management standpoint, the two species are identical and are hereafter referred to collectively as "horse clams."

Subtidal horse clams, like geoducks, fall under the resource management mandates of both the Washington Department of Fish and Wildlife (WDFW) and the Washington Department of Natural Resources (DNR). They were fished commercially in Washington from the mid-1960s to the mid-1980s using hydraulic clam harvesters, with annual landings averaging 108,000 pounds. WDFW and DNR managers stopped the fishery in the mid-1980s due to adverse public reaction to the hydraulic harvest method, not because of any biological concerns about the sustainability of the horse clam resource. No subtidal fishery for horse clams has taken place in Washington since then.

In North America, there is market demand for horse clams as bait in the Dungeness crab fishery. An Asian market for human consumption of horse clams has also been reported (Tom Bettinger, Taylor United Seafoods, personal communication).

It is easy to harvest horse clams with the standard water jet used by commercial geoduck harvesters. Indeed, they are sometimes dug accidentally by inexperienced geoduck harvesters on commercial tracts where both clams coexist. A commercial fishery for subtidal horse clams using water jets has existed in British Columbia since 1979, with the annual landings averaging about 285,000 pounds. The B.C. fishery for horse clams is restricted to those areas open for geoduck fishing. In Washington, however, WDFW and DNR have not permitted either an incidental or directed horse clam fishery using water jets. In the case of an incidental fishery for horse clams on geoduck tracts, this policy was due to the fact that no provisions for such harvests were made in the programmatic EIS for geoducks. In the case of a directed fishery, the low market value of horse clams made such a fishery economically unattractive for the two state agencies.

This situation has recently changed. First, a new programmatic EIS for geoducks is nearing completion, and it addresses the potential for an incidental horse clam fishery on geoduck tracts. As noted above, some incidental harvest of horse clams already occurs, and these clams are currently discarded on the sea floor. Secondly, several treaty tribes have expressed an interest in fishing subtidal horse clams following the federal court decision granting them a share of the shellfish resource.

The goal of this paper is three-fold: 1) to outline the existing data sources on horse clam biomass in Washington; 2) to simulate equilibrium yields of a horse clam population over a range of harvest rates; and 3) to recommend a harvest rate strategy based on this simulation, providing specific options for its implementation.

1. EXISTING DATA SOURCES ON HORSE CLAM BIOMASS

Estimates of horse clam density and biomass are available from two sources.

A. Hardshell clam surveys performed in the 1970's by WDFW divers using a venturi dredge sampler. Horse clam biomass at 47 sites totalling 5,350 acres was estimated to be 28,832,160 pounds (Goodwin and Shaul 1978). Sites ranged as far north as Point Roberts, as far west as Port Angeles, and as far south as Dyes Inlet. Because only 47 sites were sampled, this estimate represents only a portion of the state horse clam biomass. Note also that 95% confidence intervals at most sites were equal to the biomass estimates themselves.

B. WDFW geoduck surveys, which since 1984 have noted the presence or absence of horse clams within each standard 900 ft² transect. Using this presence-absence data, horse clam density can be estimated using the "stocked quadrat" method (Scheaffer *el aL* 1986) as:

$$\lambda = -(1/a)\ln(y/n)$$

where λ = density (number of horse clams per ft²)
a = area of an individual transect (900 ft²)
y = the number of transacts in which horse clams were not present
n = the total number of transacts sampled

The estimated variance of density ($V(\lambda)$) is given by:

$$V(\lambda) = (1/na^2)(e^{\lambda a} - 1)$$

Such estimates of horse clam density could easily be developed for all geoduck tracts surveyed over the past decade, as well as for those surveyed in the future.

It is to be expected that such density estimates based on presence-absence data will generally be less precise than those based on actual count data. To get a feel for the precision of such estimates, the mean density of horse clams and coefficient of variation (CV) for three randomly-selected geoduck tracts was calculated. At the Wyckoff tract in south Puget Sound, where 273 transects were sampled, the mean density was 0.0007 horse clams/ft^2, with CV = 0.09. At Tala Point in central Puget Sound, where 60 transacts were sampled, mean density was 0.0011 horse clams/ft^2, with CV = 0. 17. At Hood Head South in Hood Canal, where 30 transects were sampled, mean density was 0.0013 horse clams/ft^2, with CV = 0.23. CVs of this magnitude are probably acceptable for management, and lower bound estimates could be used if a more conservative estimate is desired.

Note that in order to estimate biomass, some estimate of weight per horse clam would have to be applied to the density estimates. This could be done crudely with a statewide approximation based on past survey work or, more precisely, by digging a sample of horse clams from individual tracts.

2. SIMULATION OF EQUILIBRIUM YIELD FOR HORSE CLAMS

A. The yield model

Horse clam yield was modeled using an age-structured equilibrium yield model (EY-MOD I) written by Dr. Jack V. Tagart of WDFW Marine Resources. Given a set of parameter estimates for mortality, maturity, growth, and selectivity, the model collapses the number of clams at age for all cohorts in the population to a single cohort, assumed to represent the stable age distribution of the population. Population size is based on an initial unfished spawning population, a declining exponential function of survival at age, and the Baranov catch equation. The model assumes continuous recruitment, the magnitude of which is governed by the Beverton-Holt stockrecruitment curve. Outputs of the model include estimates of equilbrium yield and spawning biomass per recruit for a range of fishing mortality rates. The model is available as a QUATTRO PRO spreadsheet (version 6.0 for Windows).

B. Parameter estimates

Natural mortality

Two methods were used to estimate the instantaneous rate of natural mortality (M) for horse clams. The first method relies on the empirical relationship between maximum age and mortality rate, described for molluscs, fish, and whales by Hoenig (1983) as:

$$\ln(M) = 1.44 - 0.982\ln(t_{max})$$

where t_{max} is the maximum age in years. The maximum age for two populations of *T. nuttallii* in British Columbia was 16 years (Campbell *et al.* 1990), so that $M = 0.28$ using Hoenig's method. In a commercial sample of both species from two previously unfished sites in British Columbia, the maximum age was 15 years for *T. nuttallii* and 17 years for *T. capax* (Bourne and Harbo 1987). Using Hoenig's method, $M =$ 0.30 and O.26 for these two populations. The oldest horse clam ever taken in British Columbia age samples was 24 years (Dr. Alan Campbell, personal communication), which produces an estimate of M = 0. 19.

M was also estimated using the catch curve method (Ricker 1975) and published age-frequency data from two previously unfished sites near Tofino, British Columbia (Bourne and Harbo 1987). For this analysis, the natural logarithm of frequency on age for *T. nuttallii* at both sites and *T. capax* at Comox Bar were regressed. Catch curve estimates of M were O.35,0.6l,and O.47.

I chose the lowest of all these estimates (M = 0. 19) as the best (i.e., most conservative) estimate of instantaneous natural mortality rate for horse clams.

Growth

Growth of *T nuttallii* has been well documented at two sites in British Columbia by Campbell *et al.* (1990). From that study, the von Bertalanffy growth parameters for horse clams at Newcastle Island, near Nanaimo were used, (L = 18.3 cm, K = 0.168, and t_0 = 0.51). Growth at Newcastle Island was slower than at the second site, Lemmens Inlet, near Tofino.

Length-weight relationship

The allometric log-log equation of Campbell *et al.* (1990) for Lemmens Inlet *T. nuttallii* was converted to the format $W = aL^b$ where W is total body weight in grams, L is shell length in cm, and the constants a = 0.073023 and b = 3.219001.

Maturity

Size at sexual maturity is documented for both horse clwn species in British Columbia. Campbell *et al.* (1990) found that 50% of T *nuttallii* matured at 6.8 cm, or about 3 years, near Tofino. Bourne and Smith (1972) found that *T. capax* at Seal Island became sexually mature at about 7.0 cm. For use in the equilibrium yield model, the logistic maturity-at-length relationship of Campbell *et al.* (1990) for *T. nuttallii* was converted to a simple logistic maturity-at-age curve where a = -2.47545 and b = 8.44959.

Fishery Selectivity

At two sites in British Columbia, the smallest horse clam of either species harvested by commercial divers (n = 288 clams) was 13.9 cm (Bourne and Harbo 1987). Campbell *et al* (1990) reported that "few horse clams <10.0 cm are taken" in Canadian commercial dive fisheries, and that most clams are >15.O cm. The growth and length-weight curves predict that a horse clam measuring 10.0 cm is about 5 year old and weighs 0.27 pounds, while a clam measuring 15.0 cm is roughly 11 year old and weighs 0.98 pounds. A simple logistic curve was fit by eye such that 20% of the horse clams would be selected at 5 year, and that horse clams would be fully selected at 11 year. The best-fit parameter estimates for this curve were a = -1.04827 and b = 6.669991.

Stock-recruitment (S-R) relationship

Nothing is known about the form or steepness of the stock-recruitment (S-R) relationship for horse clams. For purposes of yield modeling, the Beverton-Holt steepness parameter A was set equal to 1.0. In other words, the customary assumption of constant recruitment at all stock sizes was made. The implications of this assumption for harvest strategies are discussed below.

3. MODEL RESULTS AND HARVEST STRATEGY RECOMMENDATION

Results of the equilibrium yield modeling for horse clams are presented below in terms of five commonly-employed constant harvest rate strategies (also known as "constant F strategies). All five of these strategies set the annual quota as a linear function of biomass, applying a constant fishing mortality rate (F) to the estimate of current biomass. Two harvest strategies based on yield per recruit analysis are described (F_{max} and $F_{0.1}$), as well as three strategies based on spawning biomass per recruit analysis ($F_{35\%}$, $F_{40\%}$, and $F_{50\%}$).

The fishing mortality rate which maximizes long-term yield (F_{max}) for horse clams was 0.33. With the Beverton-Holt steepness parameter A set to 1.0, F_{max} also maximizes yield per recruit. Under this assumption (i.e., that recruitment is totally independent of stock size), F_{max} is a very aggressive fishing policy, and is not recommended as a prudent strategy.

The $F_{0.1}$ policy is often used as an alternative to F_{max}. Like F_{max}, this policy is based on yield per recruit analysis. $F_{0.1}$ is the fishing mortality rate associated with a catch rate one-tenth of the theoretical catch rate for a virgin fishery. The $F_{0.1}$, policy represents an arbitrary "backing off" from F_{max} and Deriso (1987) has shown that, in theory at least, $F_{0.1}$ is robust for a variety of S-R relationships. For horse clams, the fishing mortality rate associated with an $F_{0.1}$ policy is 0. 19.

The other three harvest rate strategies ($F_{35\%}$, $F_{40\%}$, and $F_{50\%}$) are all based on spawning per recruit (SPR) analysis. These strategies represent the fishing mortality rates which, at equilibrium, reduce the spawning biomass per recruit to 35%, 40%, and 50% of the unfished spawning biomass, respectively.

The idea behind all SPR strategies is fairly simple: since the S-R relationship for most fish stocks is unknown, the most prudent harvest strategy is one which is robust over a wide range of likely S-R relationships. Simulations made with a range of typical life history parameters and realistic S-R functions show that yield will be close to *Maximum Sustained Yield* so long as the spawning biomass is maintained somewhere in the range of about 20 - 50% of the unfished level, regardless of the form of the of S-R relationship. Within this range, both $F_{35\%}$ and $F_{40\%}$ have been recommended as risk-averse policies in fisheries where there is adequate information to place bounds on all relevant life history parameters except the S-R relationship (Mace 1994; Clark 1993).

The equilibrium model predicts that the instantaneous fishing mortality rates for horse clams associated with $F_{35\%}$, $F_{40\%}$, and $F_{50\%}$ are 0.28, 0.23, and 0. 16, respectively. Since they incorporate maturity schedules in addition to the life history processes captured by simple yield per recruit analyses, these three policies are considered superior to F_{max} and $F_{0.1}$.

The $F_{50\%}$ harvest strategy for horse clams is recommended until more research is carried out. This recommendation is made for two reasons: 1) $F_{50\%}$, is the most conservative of the three strategies, and is therefore most appropriate given our rudimentary knowledge of horse clam life history; and 2) $F_{50\%}$ is associated with an annual exploitation rate which is roughly half of F_{max}, yet produces an equilibrium yield that is only 11% less than F_{max}.

As noted above, the recommended $F_{50\%}$ harvest strategy for horse clams is attained by fishing at $F = 0.16$. This instantaneous fishing mortality corresponds to an exploitation rate (μ) of 0.135. In other words, under the $F_{50\%}$ harvest strategy, we could sustainably take 13.5% of the estimated biomass each year.

This harvest strategy could be implemented by any number of harvest tactics. Several suggested harvest tactics follow:

A. Horse clams could be fished incidentally along with geoducks in established geoduck tracts, as is done in the British Columbia fishery. The $F_{50\%}$ strategy for horse clams would entail an allowable annual exploitation rate that is nearly seven times as high as that for geoducks. Harvested geoduck tracts are re-fished only after surveys indicate that geoduck densities have recovered to prefishing levels. Empirical studies suggest that the average recovery time for such tracts is 40 year (Goodwin 1996 in press). Based on the fact that the exploitation rate for horse clams is roughly seven times that for geoducks, we may assume that horse clam populations will recover more quickly than geoduck populations on the same tract. Thus, if horse clams were taken opportunistically on established state or tribal geoduck tracts, there is little chance of overfishing them, particularly if the annual horse clam harvest did not exceed 13.5% of a region's estimated horse clam biomass. Indeed, harvesting horse clams where they coexist with geoducks might be advantageous. Goodwin (1979, 1978) describes the aggressive recruitment of horse clams and their subsequent domination of hardshell clam beds following hardshell fishing, and suggests that the same pattern might be avoided on geoduck beds if horse clams were taken as well (Goodwin 1996 in press).

This tactic is probably preferable in most areas of the state, where horse clams and geoducks coexist on at least some geoduck tracts. It is likely that all or most of the horse clams required by the market could be taken opportunistically during regular geoduck fishing. One of the major advantages of this tactic is that no separate horse clam surveys would be required. Another advantage is that horse clams which are accidentally removed from the substrate could be legally harvested. Thus, both harvesters and the state would make money on clams that are currently wasted and unreported.

B. Horse clams could be harvested as a separate fishery in the same manner as has been proposed for geoducks under recent state/tribal agreements. That is, the horse clam biomass could be estimated in each of six regions based on the survey methods outlined above. In each region, fishers could then take 13.5% of the estimated total regional biomass on an annual basis; this annual biomass would be taken from one or a few individual tracts which had been previously surveyed by methods similar to those outlined for geoducks. In other words, the entire annual quota for a region would be taken from a few discrete tracts, and the fishery would then move the following year to newly surveyed tracts; the original tracts would not be fished again until horse clam densities have returned to pre-fishing levels.

This tactic might be the preferred option in areas of the state where subtidal tracts contain only horse clams and no geoducks (or very few geoducks), such as Neah Bay. Any geoducks taken in such tracts would have to be counted against the regional geoduck harvest share. A drawback of this tactic is that horse clam tracts would have to be surveyed prior to fishing. The economic return expected from such horse clam surveys will be much lower than for geoducks.

C. Horse clams could be fished annually from discrete, surveyed beds. Under this tactic, horse clam beds could be identified and surveyed using methods similar to those used for geoducks. Such beds could then each be fished annually at 13.5% of the estimated biomass for the given bed. The chosen beds would be fished year in and year out.

This tactic, like the one above, might be optimal in areas of the state where horse clams predominate and few geoducks are found. But it also has some obvious disadvantages. First, horse clam surveys would still have to be performed, and this may prove uneconomical. Secondly, some stock assessment would be required annually to estimate the current biomass on each bed for a constant harvest rate strategy. Alternately, a constant catch strategy could be used in lieu of annual adjustments.

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revised 6/3/96

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The relative abundance of benthic animals and plants on subtidal geoduck tracts before and after commercial geoduck fishing

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INTRODUCTION

The primary objective of geoduck surveys is to estimate, prior to fishing, the mean density of harvestable geoducks within a commercial tract. Survey methodology is described in detail in Bradbury *et al.* (1997), and relies on a series of strip transects which run from the shallow commercial boundary (-18 ft MLLW) to the deep commercial boundary (-70 ft). Each strip transect is 150 ft long by six ft wide (900 ft^2) , and the survey is performed by two divers swimming side-by-side. A series of such strip transects comprises a grid line, and grid lines are spaced systematically (usually every 1,000 ft apart) throughout the commercial tract being surveyed.

Divers performing these surveys count visible geoduck siphons and record their counts at the end of each strip transect. Since 1984, divers have also recorded the presence or absence of other animals and plants observed along each transect. These data are used primarily to characterize the biota of commercial tracts for pre-fishing environmental assessments. On some commercial geoduck tracts, such presence/absence data are available not only from pre-fishing surveys, but also from post-fishing dive surveys performed after commercial geoduck fishing had been completed. Here I use presence/absence data for some of the animals and plants commonly found on geoduck tracts to answer the question: Does the relative abundance of benthic animals and plants change following commercial geoduck harvest?

METHODS AND MATERIALS

I compared, at each study tract and for each plant or animal, the proportion of all 900 ft^2 transects in which the plant or animal was present *before* fishing to the proportion of all transects in which it was present *after* geoduck fishing. The null hypothesis (H_0) was that the proportions before and after fishing were equal, and this hypothesis was tested with a 2 x 2 contingency table (Zar 1984). The tabled chi-square value for $\alpha = 0.05$ and df = 1 is equal to 3.841, and values higher than this resulted in rejection of H_0.

Dive survey data from ten commercial geoduck tracts in Puget Sound were used for this analysis (Table 1, Figure 1). These particular tracts were selected from the hundreds of surveyed tracts because they were surveyed both prior to commercial geoduck fishing and surveyed again within two years of the end of fishing. Post-harvest surveys were abandoned in 1993 (because Department of Natural Resources began on-site monitoring and weigh-outs of the commercial catch), eliminating many tracts with pre-fishing data from this analysis. Some other tracts did not receive a post-fishing survey until many years following the end of fishing, making them less useful for estimating fishing-related changes to the benthic biota. Presence/absence data on benthic biota was not collected prior to 1984, eliminating from consideration most tracts surveyed during the first 17 years of geoduck management. Post-harvest surveys were conducted at a lower intensity than pre-fishing surveys, resulting in the lower post-fishing sample sizes per tract in Table 1.

Table 1. Commercial geoduck tracts used in the analysis of relative abundance of benthic animals and plants.

Tract name	Management Region	Prefishing survey date	Period of fishing	Postfishing survey date	No. pre-fishing transects	No. post-fishing transects
Anderson Cove	Hood Canal	May 1985	1985-86	October 1988	47	14
Oak Bay 2	Central Sound	May 1985	1986-87	September 1988	13	12
Indian Island South	Central Sound	May 1985	1985-86	October 1987	15	9
Kilisut 1	Central Sound	April 1985	1986-87	September 1988	27	13
Hudson Point	Central Sound	April 1985	1986-87	September 1988	103	35
Kala Pt/Old Ft. Townsend	Central Sound	April 1985	1985-86	October 1987	47	20
Middle Point	Strait	May 1985	1986-87	September 1988	86	26
Otso	South Sound	April 1987	1988-89	May, July 1989	66	38
Crane Point	Central Sound	June 1985	1986-87	September 1988	30	16
Budd Inlet	South Sound	April 1988	1989-90	June 1990	102	31

Species (or, in some cases, taxa) of benthic plants and animals included in this analysis are shown in Table 2. Not all benthic plants and animals observed during geoduck surveys are included in this analysis. Some species were present during pre-fishing surveyes on only one or two of the ten study tracts; these were not included in the analysis because it would be impossible to discern any trends with such a small sample size. Thus, the plants and animals in this analysis represent those that are most often associated with geoducks on commercial tracts. Also not considered here are plants and animals which are too small or too cryptic to be readily observed and properly identified in all situations by divers swimming rapidly along a geoduck transect. This includes many of the small bivalve molluscs (e.g., butter clams, horse mussels, cockles, and truncated mya clams, all of which are at times difficult to see and identify by siphon characteristics alone) as well as many hydroids, bryozoans, and small gastropods. Tracts were included in the analysis for a particular plant or animal if the species was present on at least one transect either before fishing *or* after fishing. One species frequently observed on the study tracts (sea cucumber, *Parastichopus californicus*) was eliminated from the analysis because the extensive commercial dive fishery for this species would likely confound any analysis of geoduck-fishing effects.

Table 2. Species or taxons included in the analysis of relative abundance of benthic animals and plants.

Common name or taxon	Scientific name	Group	Number of tracts
Dungeness crab	*Cancer magister*	Epifauna	7
Red rock crab	*Cancer productus*	Epifauna	8
Graceful crab	*Cancer gracilis*	Epifauna	5
Sunflower star	*Pycnopodia helianthoides*	Epifauna	10
Pink short-spined star	*Pisaster brevispinus*	Epifauna	9
Flatfish	Family Pleuronectidae	Epifauna	9
Orange sea pen	*Ptilosarcus gurneyi*	Infauna	7
Sea whip	Family Virgulariidae	Infauna	3
Plumose anemone	*Metridium senile*	Infauna	8
Tube-dwelling anemone	*Pachycerianthus fimbriatus*	Infauna	6
Polychaete tube worms	*Spiochaetopterus sp. & Phyllochaetopterus sp.*	Infauna	7
Horse (gaper) clam	*Tresus sp.*	Infauna	7
Laminarian kelp	*Laminaria sp.*	Macroalgae	8

RESULTS

Epifauna

Of the seven tracts on which **Dungeness crab** (*Cancer magister*) were observed, only one tract (Crane Point) showed a statistically significant change following geoduck fishing (Appendix Table 1). On the Crane Point tract, Dungeness crab were observed on 20% of the transects prior to fishing, and 56% following fishing. When all data from the seven tracts were combined, there was a statistically significant increase in the proportion of Dungeness crab observed following fishing (17% of transects following fishing contained Dungeness crabs, compared to 9% before fishing).

Of the eight tracts containing **Red rock crab** (*Cancer productus*), only one tract (Budd Inlet) showed a statistically significant change following geoduck fishing (Appendix Table 2). On the Budd Inlet tract, red rock crab were observed on 11% of the transects prior to fishing, and 45% following fishing. When all data from the eight tracts were combined, there was no statistically significant change following geoduck fishing.

Of the five tracts on which **Graceful crab** (*Cancer gracilis*) were observed, two tracts (Otso Point and Budd Inlet) showed statistically significant changes following geoduck fishing (Appendix Table 3). The proportion of transects containing graceful crabs increased from 20% to 87% on the Otso Point tract, and from 30% to 94% on the Budd Inlet tract. When data from all the five tracts were combined, there was a statistically significant increase observed following fishing (57% of transects following fishing contained graceful crabs, compared to 20% before fishing).

On the ten tracts on which **Sunflower stars** (*Pycnopodia helianthoides*) were observed, no statistically significant changes were observed following fishing, nor were significant changes observed when the data from all ten tracts were combined (Appendix Table 4).

On the nine tracts containing **Pink short-spined stars** (*Pisaster brevispinus*), no statistically significant changes were observed following fishing, nor were significant changes observed when the data from all ten tracts were combined (Appendix Table 5).

Of the nine tracts on which **Flatfish** (Family Pleuronectidae) were observed, only two tracts (Kilisut 1 and Hudson Point) showed statistically significant changes following fishing (Appendix Table 6). The proportion of transects containing flatfish increased from zero to 31% on the Kilisut 1 tract, and from 7% to 23% on the Hudson Point tract. When data from all the nine tracts were combined, there was a statistically significant increase observed following fishing (27% of transects following fishing contained flatfish, compared to 16% before fishing).

Infauna

Of the seven tracts containing **Sea pens** (*Ptilosarcus gurneyi*), only one tract (Kala Point) showed a statistically significant change following fishing (Appendix Table 7). The proportion of transects containing sea pens increased from zero to 25% on the Kala Point tract. When data from all the seven tracts were combined, there was a statistically significant increase observed following fishing (35% of transects following fishing contained sea pens, compared to 24% before fishing).

significant change following fishing (12 tracts exhibited increases in a species or taxon, while three exhibited decreases). One taxon (horse clams) exhibited changes on three of the study tracts, while three taxa showed changes on two of the study tracts (graceful crab, flatfish, and polychaete tube worms). Six taxa exhibited changes on a single study tract (Dungeness crab, red rock crab, sea pens, plumose anemones, tube-dwelling anemones, and laminarian kelp). Two species showed no change on any of the study tracts (sunflower star and pink short-spined star). No species or taxon exhibited statistically significant changes on a majority of the study tracts in which it was present.

These data should be interpreted with caution for two main reasons: First, because no unfished "control" sites were surveyed, it is impossible to determine causality. In some cases, we noted statistically significant changes in the relative abundance of an animal or plant following geoduck fishing; but there is no way to know from these data if the change occurred *as a result* of geoduck fishing, or due to some other cause. Many of the animals and plants in this study exhibit significant shifts in abundance in the absence of geoduck fishing. Thus, significant post-fishing changes noted during this study in Washington could be mistakenly ascribed to geoduck fishing. Conversely, natural (i.e., non-fishing related) shifts in abundance might have obscured the real effects of geoduck fishing in this study.

The second caveat in data interpretation owes to the fact that only the *presence* of a particular animal or plant within a transect was noted, rather than an actual count. Presence/absence data can lead to valid estimates of density, and the technique is commonly used in forestry, wildlife management, and microbiology ("stocked-quadrat" or "frequency-index" methods; Scheaffer *et al.* 1986; Seber 1982; Cochran 1950). Density estimates could have been made for all animals and plants in this study, but these would be superfluous for the comparison of before- and after-fishing changes (i.e., the results would be identical whether comparing density or relative abundance). But density estimates from presence/absence data are rarely as precise as those based on actual counts, and the results reported here suffer from the same imprecision. Therefore, the statistical power of the contingency table tests used to detect changes following fishing is relatively low, increasing the probability of a Type II error (i.e., finding no effect when an effect occurred).

In summary, few statistically significant changes in the relative abundance of the animals and plants considered in this study were detected a year following geoduck fishing. Most (80%) of the few changes which were detected after geoduck fishing involved an increased abundance of animals or plants. These increases may have been due to geoduck fishing (related perhaps to increased availability of food or space), or may have been due to natural, non-fishing related cycles of abundance or migration.

Acknowledgements

Don Rothaus and Lynn Goodwin participated with the author on most of the post-harvest dives. Michael Ulrich provided the map and performed all the database analyses. Bob Sizemore reviewed an earlier draft.

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The effect of commercial geoduck (*Panopea abrupta*) fishing on Dungeness crab (*Cancer magister*) catch per unit effort in Hood Canal, Washington

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INTRODUCTION

Geoduck clams (*Panopea abrupta*) dominate the biomass of benthic infaunal communities in many parts of Puget Sound, Washington, and support an important commercial fishery (Goodwin and Pease 1989). Since 1971, divers have commercially fished geoducks in Washington by individually extracting them from the substrate with high-pressure water jets. Various crab species, including the large and commercially important Dungeness crab (*Cancer magister*) are common on many geoduck beds north of Vashon Island in Puget Sound (unpublished Washington Department of Fish and Wildlife [WDFW] dive survey data). Recreational crab pot fishing also occurs on some of these geoduck beds, and some crab fishers have complained that their crab fishing success declines following commercial geoduck harvest.

The objective of this study was to determine if there was a significant effect of commercial geoduck fishing on Dungeness crab fishing catch-per-unit-effort (CPUE). We sampled crabs using baited pots at one site before, during, and after commercial geoduck fishing. Concurrently, we sampled crabs at a nearby unfished site. Both sites were sampled 20 times over a period of 4.6 years. Specifically, we wanted to determine if significant changes in crab CPUE occurred following geoduck fishing in the treatment site, and if any such changes could be attributed to geoduck fishing.

METHODS

Experimental Design

Two sites, a treatment site and a control site, were experimentally fished with crab pots in order to determine if geoduck fishing had an effect on Dungeness crab fishing success. The observed random variable was crab CPUE, the number of crabs caught per pot. The treatment site was sampled both before and after commercial geoduck fishing in order to test the primary null hypothesis: H_0: $\mu_{before} = \mu_{after}$, where μ_{before} = mean CPUE of all pre-fishing samples, and μ_{after} = mean CPUE of all post-fishing samples.

Crab CPUE at the treatment site could be affected both by fishing effects (the direct or indirect consequences of geoduck fishing) and non-fishing effects (environmental, seasonal, or crab behavioral effects not related to geoduck fishing). Non-fishing effects at the treatment site might mask the effects of geoduck fishing, causing acceptance of H_0 and a Type II error. Conversely, non-fishing effects at the treatment site might be mistaken for fishing effects, causing rejection of H_0 and a Type I error. Thus, an unfished control site was sampled concurrently with the treatment site in order to account for non-fishing effects affecting crab CPUE.

This comparison between control and treatment sites assumed that crab CPUE at both sites was equally affected by non-fishing effects. This assumption and other hypotheses had to be tested prior to a test of H_0 at the treatment site, as outlined in the sequence below:

Step 1. Test the assumption that crab CPUE at the control site and treatment site are equally affected by non-fishing effects.

This assumption was tested with a test on the correlation coefficient ρ (Sokal and Rohlf 1981). Specifically, we tested the hypothesis that $\rho > 0$, with the variables x_i = estimated CPUE at the control site for the i = 1-10 pre-fishing samples, and y_i = estimated CPUE at the treatment site for the i = 1-10 pre-fishing samples. If $\rho \leq 0$, then correlation was either nonexistent or negative, implying that the control site was not a reliable analog of the treatment site in terms of non-fishing effects. Without being able to "tease out" non-fishing effects at the treatment site, we would be unable to determine if fishing effects had occurred, and the experiment would be terminated. If, on the other hand, $\rho > 0$, we could conclude that the two sites were positively correlated, and that therefore the control site was a reliable estimator of non-fishing effects at the treatment site. However, $\rho > 0$ does not necessarily imply strong correlation. Therefore we established an arbitrary guideline for "strong" correlation and tested the hypothesis that $\rho \geq 0.70$. If we failed to reject this hypothesis,we continued to Step 2.

Step 2. Test whether non-fishing effects differed during the pre-fishing and post-fishing periods.

Following acceptance of the assumption that the control and treatment sites are equally affected by non-fishing effects (Step 1), the control site provides a basis for this test, since no fishing occurred there during either period. We can test the hypothesis H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where μ is mean crab CPUE at the control site. If H_0 is not rejected, no significant changes occurred, and we proceed to Step 3. If, on the other hand, H_0 is rejected, then a significant change due to non-fishing effects occurred at the control site between the two time periods which must be taken into account at the treatment site, and we proceed to Step 4.

Step 3. Failing to reject H_0 in Step 2, we would conclude that there are no changes in non-fishing effects between the pre- and post-fishing time periods. In this step we can then proceed to directly test whether CPUE changed in the treatment area following geoduck fishing, and significance will imply an effect due to geoduck fishing rather than environmental, seasonal, or behavioral effects. We test the primary hypothesis, H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where μ is the mean crab CPUE at the treatment site. Rejection of H_0 would imply an effect due to geoduck fishing.

Step 4. Rejecting H_0 in Step 2, we would conclude that there are significant changes in non-fishing effects between the pre- and post-fishing time periods which must be accounted for in hypothesis tests of the treatment site. As in Step 3, we again test the primary hypothesis, H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where μ is the mean crab CPUE at the treatment site, but we now require a modification of the means test in order to "tease out" the significant changes due to non-fishing effects.

We first followed the above testing sequence using the estimated CPUE of all Dungeness crabs. Then we performed the sequence again, using only the estimated CPUE of Dungeness crabs which may be legally taken by sport and commercial crabbers (i.e., male Dungeness crabs with a carapace width > 151 mm).

Site Description

Two sites along the western shore of northern Hood Canal were chosen for the experiment (Figure 1). Thorndyke Bay, located at 47° 48' 22" N 122° 44' 15" W, was chosen as the treatment site because a commercial geoduck harvest was scheduled to start there in August 1992. Commercial divers landed 1.8 million pounds of geoducks from the treatment site during the period of this experiment. South Point, located at 47° 49' 27" N 122° 41' 57" W, was chosen as the unfished control site because of its proximity to Thorndyke Bay, which lies about 1.8 km to the south. South Point was surveyed by WDFW divers in 1986, but has never been fished commercially for geoducks.

WDFW geoduck dive surveys in 1986 and 1990 indicated that Dungeness crab occurred at both sites. During these surveys, divers at the treatment site (Thorndyke Bay) sighted Dungeness crabs on 12% of all transects. At the control site (South Point), divers sighted Dungeness crabs on 17% of the transects. Neither site was fished commercially for crabs during the course of this experiment. Both sites are open for recreational crab fishing, and recreational crab pots were observed at both sites during portions of the study. Substrate at both sites is comparable, a mix of roughly equal parts sand and mud, and is typical of commercial geoduck beds.

Each of the two sites was divided into a northern half and a southern half to facilitate the use of 30 crab pots over a two-day sampling period as described below. Distance between the northern and southern portions of each site was approximately 30 m. Total area of the control site (northern and southern halves combined) was roughly 16,700 m^2. Total area of the treatment site (northern and southern halves combined) was roughly 33,400 m^2. The difference between the areas of the two sites was due to differences in bottom contours; the length of each site (i.e., the distance along the shoreline) was identical, but because crab pots were placed along depth contours (see below), the more gently sloping bottom contour at the treatment site increased its width (i.e., distance from the shoreline) relative to the control site.

Crab Sampling Methods

Both the control and treatment sites were sampled for crab CPUE over a period of 4.6 years, from December 1990 through July 1995. During this period, each of the two sites was sampled on 20 occasions, and both of the two sites were sampled on the same days. Sampling dates are shown in Table 1.

The first ten samples at both sites were taken prior to any geoduck fishing. Commercial geoduck fishing began at the treatment site in August 1992. No geoduck fishing occurred at the control site, either before or during this experiment.

At the treatment site, the commercial geoduck fishery took place during two distinct seasons, from August 1992 through December 1992, and from June 1993 through December 1994. During the five-month period from January 1993 through May 1993, geoduck fishing was closed in the treatment site. For purposes of this analysis, we considered all samples taken after the commercial geoduck fishing began in August 1992 to be "post-fishing" samples. Thus, "post-fishing" samples included three samples taken during the first fishing season, two during the five-month hiatus between fishing seasons, and two during the second fishing season. Thus, there were ten pre-fishing samples spanning 1.6 years, and ten post-fishing samples spanning 3.0 years. Note that we use the term "post-fishing samples" for simplicity's sake when referring to both the treatment and control sites, although no fishing took place in the control site.

Each sample consisted of three consecutive days during which crab pots were set and retrieved. On the first day, 15 commercial crab pots were set in the northern half of each site and allowed to soak overnight for an average of 22 hrs. At each site, five of the 15 pots were set at -20 ft MLLW, five were set at -40 ft MLLW, and five were set at --55 ft MLLW. This depth range was chosen because the commercial geoduck fishery takes place between -18 ft MLLW and -70 ft MLLW. Along each of these depth contours, the five pots were positioned roughly 30 m apart. Each pot was baited with about 0.7 kg of frozen geoduck meat. On the second day of each sample, the pots were pulled at each site and the crabs caught were sampled and released. Pots were then re-baited and reset in the southern half of each site, along the same depth contours and with the same approximate spacing. Following a second overnight soak which averaged 22 hours, the pots were again recovered, and the crabs sampled and released. Bait removed from pots following fishing was always kept aboard and discarded well away from the test sites.

During some of the sampling, stormy weather or equipment problems prevented timely collection of some crab pots. This resulted in some pots soaking for a longer time than others. In such cases, we eliminated these pots from data analysis.

To avoid conflicts with the commercial geoduck fishing fleet, all samples taken during the two fishing seasons were made during the weekends, when the fishery was closed.

The crab species, sex, carapace width, and shell condition (new molt, soft shell, hard shell, old shell) were noted for each crab caught. In addition, the presence or absence of external embryos was recorded for all female crabs. Individual crab weights were taken during eight of the samples.

RESULTS

Table 1 and Figures 2 and 3 show how the estimates of Dungeness crab CPUE varied at the control and treatment sites during the 4.6 years of the experiment. Estimated CPUE for total Dungeness crab was higher at the control site than at the treatment site throughout the pre-fishing period (unpaired t-test of equality of means assuming equal variance, $t = 3.86$, $\alpha = 0.05$, $df = 18$, $P = 0.0012$, two-tailed test; F-test of equality of variances, $F = 3.179$, $\alpha = 0.05$, $df = 9,9$). Estimated CPUE for total Dungeness crab was not significantly higher at the control site than at the treatment site throughout the post-fishing period, however (unpaired t-test of equality of means assuming equal variance, $t = 1.81$, $\alpha = 0.05$, $df = 18$, $P = 0.0867$, two-tailed test; F-test of equality of variances, $F = 1.807$, $\alpha = 0.05$, $df = 9,9$).

Mean estimated CPUE at the treatment site prior to geoduck fishing was 1.70 Dungeness crabs/pot, and was 2.96 crabs/pot during the post-fishing period. At the control site, mean estimated CPUE prior to fishing was 4.79 crabs/pot, and post-fishing estimated CPUE was 4.85 crabs/pot. When only legal crabs (males > 151mm carapace width) were considered, mean pre-fishing and post-fishing estimated CPUEs at the treatment site were 1.24 and 2.31 crabs/pot, respectively. At the control site, mean pre-fishing and post-fishing estimated CPUEs for legal crabs were 3.20 and 3.53 crabs/pot, respectively.

The first assumption to be tested in Step 1 of the experimental design was that the control and treatment sites were equally affected by seasonal and environmental variables. This assumption was examined with a test on the correlation coefficient ρ (Sokal and Rohlf 1981). Specifically, we tested the null hypothesis H_0: $\rho = 0$, where x_i = estimated Dungeness crab CPUE at the control site for the i = 1-10 pre-fishing samples, and y_i = estimated Dungeness crab CPUE at the treatment site for the i = 1-10 pre-fishing samples. The null hypothesis of no correlation was rejected (r = 0.8339, α = 0.05, df = 8, P = 0.0010). A non-parametric correlation test also demonstrated a statistically significant correlation between control and treatment sites during the pre-fishing period (Spearman rank test, r_s = 0.806, α = 0.05, n = 8, P = 0.0032). We performed the same two tests on CPUE data for legal Dungeness crabs and got similar results (r = 0.8738, α = 0.05, df = 8, P = 0.0003; r_s = 0.818, α = 0.05, n = 8, P = 0.0023). We used Fisher's transformation (Zar 1984) to set confidence limits on the estimate of ρ for total Dungeness crab at the control and treatment sites. The asymmetric 95% confidence bounds on the estimate r (= 0.8339) were $0.4301 < r < 0.9595$. Based on the rejection of H_0 in these correlation tests and a lower confidence bound on ρ that is not unreasonably low, we were willing to accept the first assumption of equal non-fishing effects in the control and treatment sites.

Next, we proceeded to Step 2 and tested whether crab CPUE differed in the control site before and after geoduck fishing in the treatment site. Specifically, we tested the null hypothesis H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where $\mu_{pre\text{-}fishing}$ is the mean crab CPUE (number of total Dungeness crab/pot) during the pre-fishing period at the control site, and $\mu_{post\text{-}fishing}$ is the mean CPUE during the post-fishing period at the control site. Variances about the two estimated mean CPUEs were not significantly different (F-test, F = 1.258, α = 0.05, df = 9,9), so an unpaired t-test assuming equal variance was used to test the equality of the two means. There was no statistically significant difference between pre- and post-fishing periods (unpaired t-test with equal variance, t = -0.06, α = 0.05, df = 18, P = 0.95, two-tailed test). We performed the same test with CPUE data for legal Dungeness crabs and got a similar result (F-test, F = 1.749, α = 0.05, df = 9,9; unpaired t-test with equal variance, t = -0.45, α = 0.05, df = 18, P = 0.66, two-tailed test). These results suggest that there were no non-fishing effects occurring in the control area which would have to be "teased out" of the treatment area in the post-fishing period. In other words, we could assume that statistically significant changes following fishing in the treatment area, if any, could be attributed to geoduck fishing and not environmental "noise."

Thus, we proceeded to Step 3 and tested the primary hypothesis, whether crab CPUE in the treatment site differed following geoduck fishing. Specifically, we tested the null hypothesis H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where $\mu_{pre\text{-}fishing}$ is the mean crab CPUE (total Dungeness crab/pot) during the pre-fishing period at the treatment site, and $\mu_{post\text{-}fishing}$ is the mean CPUE during the post-fishing period at the treatment site. Variances about the two mean CPUEs were significantly different (F-test, F = 4.560, α = 0.05, df = 9,9), so an unpaired t-test assuming unequal variance was used to test the equality of the two means. There was no statistically significant difference in crab CPUE between pre- and post-fishing periods at the treatment site (unpaired t-test with unequal variance, t = -1.36, α = 0.05, approximate df = 12, P = 0.20, two-tailed test). The same tests were performed using CPUE data for legal Dungeness crab with similar results (F-test, F = 3.709, α = 0.05, df = 9,9; unpaired t-test with equal variance, t = -1.59, α = 0.05, df = 18, P = 0.13, two-tailed test).

By failing to reject H_0 in Step 3, we concluded that there were no significant effects on crab CPUE which could be attributed to geoduck fishing at the treatment site in Thorndyke Bay.

We estimated the statistical power (1-β) of the experiment using CPUE data for total Dungeness crabs at both the control and treatment sites. First, we estimated the power of the two-sample t-test at the control site to detect a change in mean CPUE of ± 50%. We assumed sample sizes $n_1 = n_2 = 10$ as in our experiment, and $\alpha = 0.05$ (two-tailed), and used the power test outlined in Zar (1984). Since mean CPUE at the control site throughout the experiment was 4.82 crabs/pot, we were therefore estimating the probability of detecting a true difference of ± 2.41 crabs/pot from this mean level. A value of $\phi = 1.82$ and $\nu = (n_1 + n_2) - 2 = 18$ was associated with a power (1-β) of about 0.65. Thus, our experiment had only a 65% chance of detecting a 50% change (either an increase or a decrease) in total Dungeness crab CPUE at the control site.

Similarly, we estimated the minimum difference in mean CPUEs at the control site which we would detect with a power of 0.90, given the sample sizes above and $\alpha = 0.05$. The minimum difference which we would have a 90% chance of detecting was 3.22 crabs/pot. Since the mean CPUE at the control site during the entire experiment was 4.82 crabs/pot, CPUE would have to increase or decrease at least 67% before we would have a 90% chance of detecting it with our experimental methods.

We also estimated power of the two-sample t-test at the treatment site. The power of the test to detect a change in mean CPUE of ±50% was almost zero at the $\alpha = 0.05$ significance level. The minimum difference in mean CPUE that would be detected with a power of 0.90 was 3.00 crabs/pot. Mean CPUE at the treatment site prior to geoduck fishing was 1.70 crabs/pot, so the minimum detectable difference amounts to 176% of the average CPUE.

The same power tests were performed using CPUE data for legal Dungeness crab with similar results. The power (1-β) of the two-sample t-test to detect changes in mean CPUE for legal Dungeness crabs of ±50% at the control site was 0.55. The minimum difference in mean CPUEs at the control site which we would have a 90% chance of detecting was 2.54 legal crabs. Since the mean CPUE at the control site during the entire experiment was 3.36 legal crabs/pot, CPUE would have to increase or decrease at least 76% before we would have a 90% chance of detecting it with our methods. At the treatment site, power of the test to detect changes of ±50% in legal Dungeness CPUE was almost zero, and the minimum detectable difference with a power of 0.90 was 189% of the average pre-fishing CPUE.

DISCUSSION

This study tested the effects of geoduck fishing on crab CPUE (i.e., the number of crab per pot), not on the absolute abundance or density of crabs. Although crab CPUE may be a valid estimator of crab abundance or density, we did not make this assumption nor test it. Confining our results to crab CPUE in this way is appropriate, because the impetus for this experiment was the frequent complaint of recreational crabbers that their catch rate (i.e., the number of crabs per pot) declines following commercial geoduck fishing. Estimating CPUE with crab pots as we did is perhaps more relevant to the question posed by recreational crabbers than attempting to directly estimate crab abundance or density. Indeed, we can construct plausible scenarios whereby crab CPUE could be altered by geoduck fishing due to crab feeding behavior changes, even as abundance or absolute density of crabs in the area remains stable. Our results, however, suggest that there is no statistically significant change in CPUE following geoduck fishing.

Implicit in our experimental design were several assumptions which could not be statistically tested. The first of these assumptions was that crabs caught during each sample represented a random sample of the crab population, and were independent of previous samples. The average time between two samples was 88 days, and the minimum time between samples was 28 days. Crabs are highly mobile, moving in search of food and migrating due to reproductive and molting cues. Cleaver (1949) reported that tagged crabs released at Grays Harbor, Washington, traveled an average of 14 km in three months, which was the average time between samples in this study. The combination of crab motility and a lengthy period between samples tends to support our assumption that crabs randomly mixed in the population between sampling occasions.

A second related assumption is that handling mortality of crabs was negligible during the experiment, or else equal at both sites. Dungeness crabs, except when soft-shelled immediately following a molt, are not easily harmed by normal handling. In any case, since handling procedures were identical at both sites, it is likely that any mortality would have affected the results equally at both sites.

A third assumption is that crab catch during the first day of a sample (i.e., when the northern half of each site was sampled) did not affect crab CPUE during the second day, when the southern half was sampled. We do not know how far crabs move in order to feed, but it is likely that at least some crabs moved from one half of the plot to the other half during the two days of each sample period. We also do not know if crabs become "trap-shy" or, conversely, if they become dependent on pots for food. Such behavior would be of concern if we were attempting to estimate absolute abundance or density of crabs, but is of lesser concern in this experiment, which estimates CPUE. It is likely that such behavior, if it affected the experimental results at all, would have affected both sites equally.

The results of this test revealed a high level of natural variability in crab CPUE. Possible reasons include the migratory nature of crabs, which move onshore and offshore in response to molting and reproductive cues. Other possible factors include cyclic abundance patterns and behavioral changes related to food availability. Commercial catch rates of Dungeness crabs in Washington, Oregon, and California have historically been highly unstable, and have been correlated with a number of abiotic and biotic factors (Methot 1989). In addition, crab CPUE in our experiment could have been affected by recreational crabbing which occurred at both sites. During WDFW sport crab surveys, crab pots were observed at the treatment site in August and October 1991, and at the control site in October and November 1993, as well as in February and March 1994. This recreational crabbing may have been partly responsible for the apparent decline in estimated CPUE at the control site between samples 16 and 17, a period during which estimated CPUE at the treatment site increased.

This high natural variability in crab CPUE reduced the statistical power of the experiment. Although we detected no significant change in crab CPUE following geoduck fishing at the treatment site, power analysis revealed that CPUE would have to increase or decrease roughly 176% before we would have a 90% chance of detecting the change. We sampled the site 20 times during 4.6 years with 30 crab pots on each occasion, so from a practical sampling standpoint, this low level of statistical power is probably unavoidable. We can expect that such natural variability in crab CPUE would also affect recreational crabbers, and probably to a much greater degree since they are limited in the number of "samples" they can take. Therefore, anecdotal reports which allege that commercial geoduck fishing drastically reduces crab catches cannot be given much credence.

ACKNOWLEDGEMENTS

We thank Tom Cain, L. Goodwin, D. Herren, B. McLaughlin, J. Odell, P. Roni, D. Rothaus, B. Sizemore, L. Timme, and B. Wood for many days of help baiting, setting, and retrieving crab pots. A. Hoffmann and J. Tagart provided biometric guidance and helpful reviews of an early draft.

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Table 1. Results of Dungeness crab sampling at the control and treatment sites in Hood Canal. "Pre-fishing" refers to sample numbers 1-10, "post-fishing" refers to sample numbers 11-20. Legal crab refers to males > 151 mm carapace width.

			CONTROL					TREATMENT				
			CATCH		EFFORT	CPUE (NUMBER CRABS/POT)		CATCH		EFFORT	CPUE (NUMBER CRABS/POT)	
sample	date	time (days)	TOTAL CRAB	LEGAL CRAB	NUMBER OF POTS	TOTAL CRAB	LEGAL CRAB	TOTAL CRAB	LEGAL CRAB	NUMBER OF POTS	TOTAL CRAB	LEGAL CRAB
1	12/12/90	0	44	26	24	1.83	1.08	17	8	24	0.71	0.33
2	03/15/91	93	148	121	24	6.17	5.04	62	49	24	2.58	2.04
3	04/19/91	128	153	116	24	6.38	4.83	69	57	24	2.88	2.38
4	07/03/91	203	257	185	30	8.57	6.17	113	74	30	3.77	2.47
5	08/22/91	253	74	20	30	2.47	0.67	22	12	30	0.73	0.40
6	10/17/91	309	188	93	30	6.27	3.10	36	18	30	1.20	0.60
7	12/13/91	366	106	64	30	3.53	2.13	20	17	30	0.67	0.57
8	02/28/92	443	157	113	30	5.23	3.77	92	75	30	3.07	2.50
9	06/11/92	547	160	117	30	5.33	3.90	33	29	30	1.10	0.97
10	07/30/92	596	58	34	27	2.15	1.26	9	3	30	0.30	0.10
11	09/27/92	655	63	40	15	4.20	2.67	9	4	15	0.60	0.27
12	11/15/92	704	148	108	30	4.93	3.60	31	21	29	1.07	0.72
13	12/13/92	732	114	90	30	3.80	3.00	46	38	30	1.53	1.27
14	02/25/93	806	202	140	30	6.73	4.67	138	121	30	4.60	4.03
15	05/07/93	877	176	111	30	5.87	3.70	77	68	30	2.57	2.27
16	06/26/93	927	263	195	30	8.77	6.50	51	43	30	1.70	1.43
17	06/19/94	1285	162	130	30	5.40	4.33	281	191	30	9.37	6.37
18	02/28/95	1539	124	98	30	4.13	3.27	143	120	30	4.77	4.00
19	05/03/95	1603	65	51	30	2.17	1.70	45	37	30	1.50	1.23
20	07/12/95	1673	75	56	30	2.50	1.87	56	46	30	1.87	1.53
MEAN (PRE-FISHING)			134.50	88.90		4.79	3.20	47.30	34.20		1.70	1.24
MEAN (POST-FISHING)			139.20	101.90		4.85	3.53	87.70	68.90		2.96	2.31

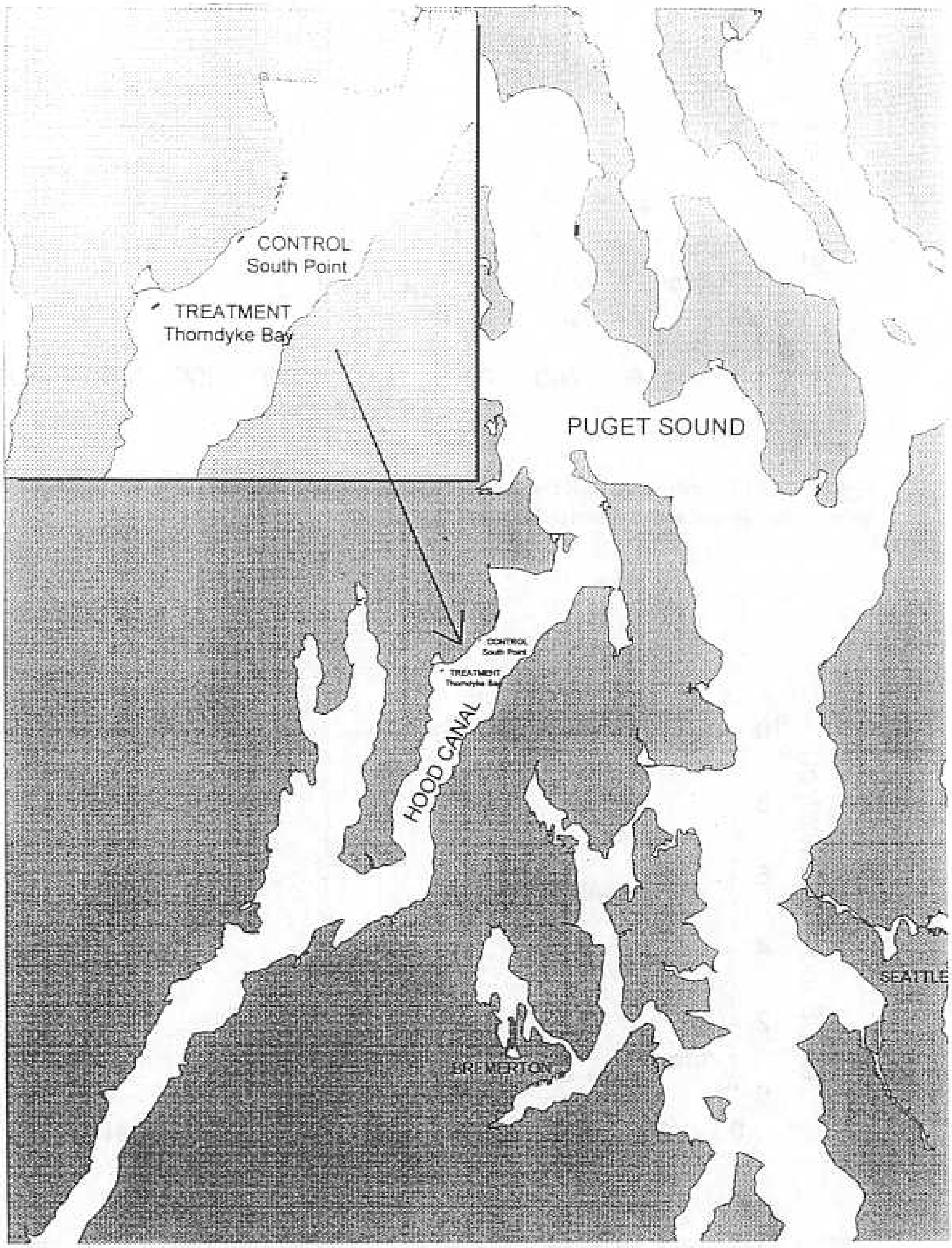

Figure 1. Location of the control and treatment sites in northern Hood Canal which were sampled for Dungeness crab catch per unit effort.

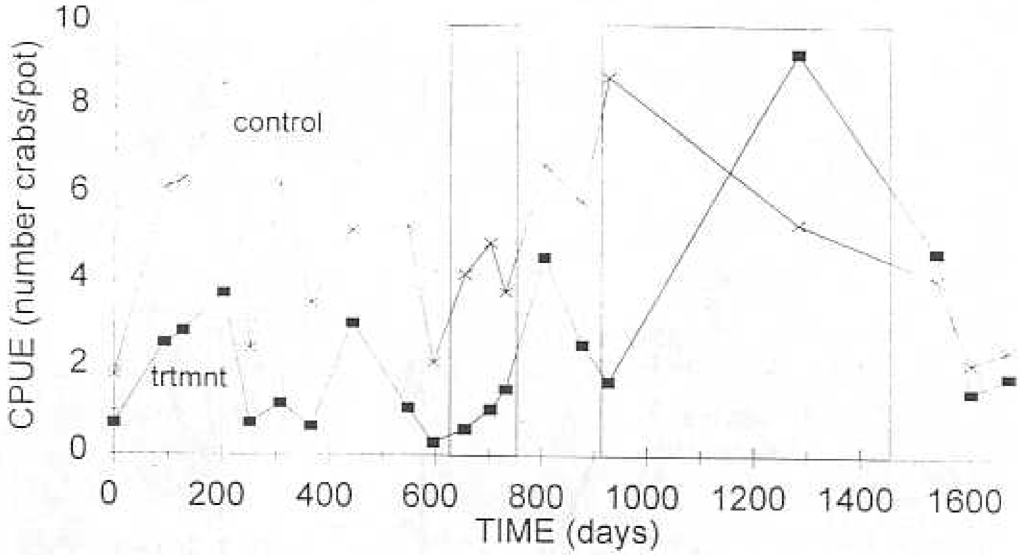

Figure 2. CPUE (crabs/pot) of all Dungeness crabs at the control and treatment sites. Shaded areas indicate the two periods of commercial geoduck fishing.

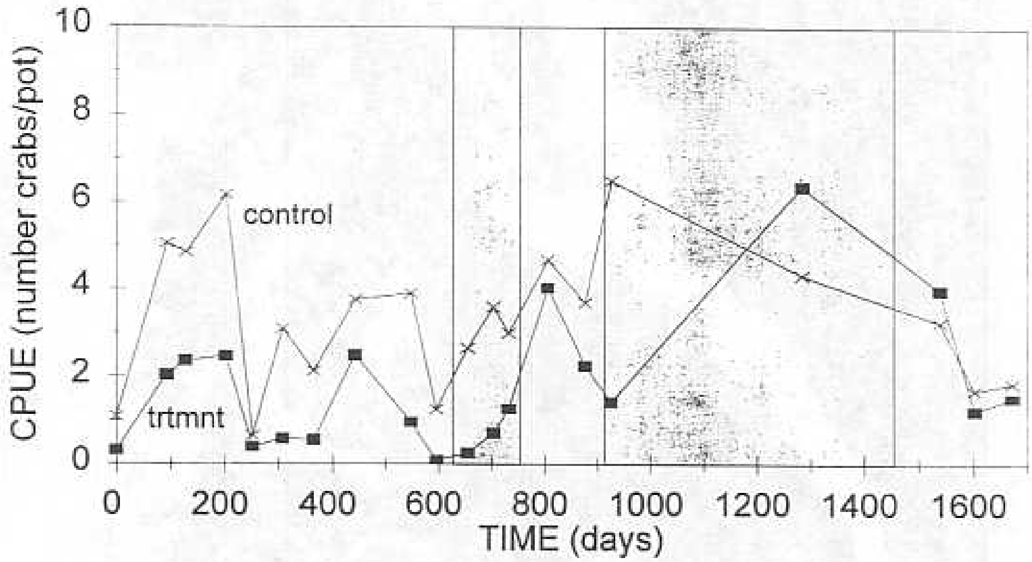

Figure 3. CPUE (crabs/pot) of legal Dungeness crabs at the control and treatment sites. Shaded areas indicate the two periods of commercial geoduck fishing. Legal crabs are males > 151 mm carapace width.

Appendix 2

The time between successive crops (recovery time) of subtidal geoducks (*Panopea abrupta*) in Puget Sound, Washington

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INTRODUCTION

The annual Total Allowable Catch (TAC) for the commercial geoduck clam (*Panopea abrupta*) fishery in Washington is calculated by applying an annual harvest rate to estimates of the commercially harvestable biomass. The annual harvest rate was based on a Ricker yield-per-recruit (YPR) model until 1997, when managers began using an age-based equilibrium yield model, which framed its predictions in terms of spawning-biomass-per-recruit (SPR). The original YPR model resulted in a constant-catch strategy with the annual harvest rate equal to 2% of the unfished biomass ($2\%B_0$). The current harvest rate strategy ($F_{40\%}$) is predicted to preserve 40% of the unfished spawning biomass, resulting in a constant harvest rate of 2.7% of the current commercial biomass ($2.7\%B_t$). Details of the stock assessment procedure and equilibrium yield model are contained in Bradbury and Tagart (2000) and Bradbury *et al.* (1997). TACs are calculated annually for each of six management regions in Washington. The entire regional TAC is harvested in a few discrete commercial tracts each year, and the TAC in subsequent years is taken from other tracts. The fishing strategy is therefore a form of periodic (rotational) harvest. Once fished, a tract is not re-fished until surveys demonstrate that it has returned to its pre-fishing levels of geoduck density and biomass.

Both the former YPR and current equilibrium yield models belong to the group of so-called "structural" models. Structural models represent fish populations in some simplified way which nevertheless captures their essential dynamics. In such models, variables usually include estimates of natural mortality, growth, sexual maturity, and fishery selectivity. A major practical advantage of structural models is that they allow managers to make predictions about yield and spawning biomass for a wide range of harvest rates *before* actually applying those harvest rates.

Structural models also have many disadvantages, however. All the variables are estimated with some degree of error, and many rely on untested assumptions. For example, both the YPR and equilibrium yield models for geoducks rely on catch-curve estimates of natural mortality, which in turn rely on untested assumptions regarding constant recruitment and constant mortality across all age classes. Growth and mortality parameters are estimated from unfished populations, even though it is acknowledged that they may be affected by fishing. More importantly, nothing is known about the stock-recruitment relationship for geoducks. Consequently, both models have assumed that recruitment is independent of the stock across all stock levels. Structural models are also necessarily limited in the number of variables they include. The geoduck models, for example, do not take into account environmental or climactic changes which may affect geoduck populations.

An alternative to structural modeling is empirical modeling. Empirical (or heuristic) models ignore the underlying factors which influence population dynamics, focusing instead on how a fished population fluctuates over time. This *post hoc* approach precludes the use of empirical models prior to fishing, or in the early stages of a fishery. But empirical models have great utility as a test of structural models. Once a fishery is underway, for example, empirically observed changes in the population can be compared with the predictions of a structural model as a method of "ground truthing." Moreover, the predictions from an empirical model implicitly include all the factors which influenced the population during the observation period (including recruitment, environmental and climactic changes).

Here we use a simple empirical model to estimate the time required for commercially fished geoduck populations to recover to their pre-fishing levels. We then compare these empirical results with the harvest rate predictions of structural models used to manage the geoduck fishery.

METHODS

Geoduck densities in 15 separate commercial tracts were estimated from diver surveys before fishing, shortly after fishing, and again after several years of no fishing. A recovery rate for each tract was estimated from the difference in density between the first post-fishing survey and the second post-fishing survey. The time for fished geoduck populations to recover to their pre-fishing density was then estimated, assuming that the observed recovery rate would remain the same until pre-fishing density was attained.

The commercial tracts involved in this study are shown in Figure 1. Study tracts were chosen opportunistically (rather than randomly or systematically) from among the many surveyed and commercially-fished tracts in Puget Sound. Study tracts were chosen which met all the following criteria: 1) Tracts which included adequate positioning information for each transect; 2) Tracts where the first post-fishing survey was made within one year of the end of fishing; 3) Tracts where the pre-fishing and first post-fishing survey occurred during the seasonal period of high "show" factor (Goodwin 1977), and; 4) Tracts which were roughly representative of the geographic spread of commercial tracts in Puget Sound. Tracts which met these four criteria were included in the study and scheduled for a second post-fishing survey.

Standardized geoduck survey methods used throughout the study are described in detail by Bradbury *et al.* (1997). In these surveys, two divers count geoduck siphon "shows" within a series of 900 ft^2 strip transects. One exception in this study to the established survey procedures is that density estimates were not adjusted with a "show" factor. "Show plots" used in many of the pre-fishing surveys were no longer physically intact or considered reliable at the time of the second post-fishing surveys. For this reason, only the unadjusted diver counts of geoducks for each transect were used in estimating density. These density estimates therefore underestimate the actual geoduck density, but are assumed to be comparable as relative indices of abundance from survey to survey. The "show" factor for a given site varies seasonally (Goodwin 1977). To reduce possible survey-to-survey variability due to the show factor, we attempted to synchronize the seasonal timing of post-harvest surveys. For example, if the first post-harvest survey at a particular site was conducted during the first week of June, we attempted to conduct the second post-fishing survey during the first week of June.

Pre-fishing surveys were completed from 1972-85, depending on the tract. Most of the pre-fishing surveys were conducted in 1983-85. The second post-fishing surveys were conducted during the spring and summer of 1992, 1993, and 1994.

The number of geoducks observed within each transect was recorded for the pre-fishing and post-fishing surveys at each tract. The data were log-normalized, and the log-transformed data were analyzed with a student's t-test to determine if statistically significant differences in the mean density existed between surveys on a given tract All t-tests were carried out at the $\alpha = 0.05$ significance level and assumed unequal variances. At each site, the first t-test was performed to determine if significant differences existed between the pre-fishing mean density and the first post-fishing mean density. We assumed that any significant differences between the two densities were due entirely to commercial fishing. Given the low natural mortality rate of geoducks ($M = 0.0226$, Bradbury *et al.* 1997) and the fact that the first post-fishing survey was conducted within a year of the end of fishing, this is a reasonable assumption. A second t-test was then performed comparing the mean densities of the first and second post-fishing surveys. Significant differences in this case would be due to post-fishing recruitment.

The observed rate of recovery (in terms of density) from the first post-fishing survey to the second post-fishing survey was calculated as:

$$r = \Delta t \, / \, (D_2 - D_1) \qquad (1)$$

where r = rate of recovery

Δt = time (in yr) between first post-fishing and second post-fishing surveys

D_1 = mean density of first post-fishing survey

D_2 = mean density of second post-fishing survey

Assuming that r remains constant, the projected time to recover from the observed post-fishing density to the pre-fishing density is given by:

$$T = r\,(D_0 - D_1) \qquad (2)$$

where T = time (in yr) to recovery from the observed post-fishing density
D_0 = mean density of the pre-fishing survey

Commercial tracts are never fished down completely (i.e., until density = 0), and the observed post-fishing density differs for each tract, depending on both the initial density and the tract-specific harvest rate. To standardize recovery time over all the tracts, we calculated the time for each tract to recover to pre-fishing density if *all* harvestable geoducks had been removed from the tract:

$$T_{100\%} = r\,D_0 \qquad (3)$$

where $T_{100\%}$ = time (in yr) to recovery assuming complete removal of all geoducks

The mean $T_{100\%}$ for all tracts was calculated and used to predict optimum annual harvest rates which corresponded to the constant-catch and constant harvest rate strategies currently used in managing the geoduck fishery. Fishery models frame their predictions in terms of biomass, whereas the recovery study data are in terms of density. Geoducks, however, grow rapidly and reach asymptotic between the ages of 10 - 20 yr (Goodwin 1976; Bradbury *et al.* 1997). If mean recovery times were < 10 - 20 yr, then density would likely underestimate biomass to some degree. But as long as mean recovery time > 20 yr, the difference between density and biomass is negligible. Thus, for the following comparisons, we use the two terms interchangeably. Likewise, many of the comparisons between model predictions and results of the recovery study treat total biomass and spawning biomass as the same thing. Given the young age at which geoducks become sexually mature, the difference between total and spawning biomass will be less than 1% (Bradbury *et al.* 1997) and can therefore be ignored.

The optimum constant-catch harvest rate (harvest rate as a proportion of *unfished*, "virgin" biomass B_0) is given by:

$$\mu_{constant\text{-}catch} = 1 / T_{100\%} + 1 \qquad (4)$$

The effects of a constant harvest rate strategy (μ, or harvest rate as a proportion of *current* biomass B_t) were explored using two simple biomass dynamics models. The first model assumed linear recovery after fishing, while the second model assumed logistic recovery after fishing. Both models were initiated in year 0 by setting unfished biomass B_0 equal to 10,000 units, divided into 100 "tracts," each tract containing a biomass $b_{x,0}$ of 100 units. In the first year of fishing ($t = 1$), the annual catch was equal to μB_0. In both models, biomass on tracts beginning with the first tract were reduced in sequence until a total catch equal to μB_0 had been removed. In the linear model, it was possible to reduce tracts to zero biomass; the logistic model required at least a small amount of residual biomass to remain on a fished tract following harvest.

Following the first year's harvest ($t = 2$), biomass was constrained to remain stable (i.e., $b_{x,2} = 100$) on all unfished tracts, but was allowed to recover on fished tracts according to either a linear or logistic model. In the linear model, biomass recovered each year by a constant amount equal to $b_{x,t}$ $(1/T_{100\%})$ until tract biomass again reached the unfished biomass level of 100. In the logistic model, biomass on a fished tract b_x in each subsequent year was given by:

$$b_{x,t+1} = b_{x,t} + r\, b_{x,t}\,(1 - b_{x,t} / K) \qquad (5)$$

where K is the carrying capacity (the unfished tract biomass, in this example 100 units per tract) and r is the intrinsic rate of population growth in the logistic model. We chose r by iteration, assigning it the value which allowed tract biomass to recover to $K = 100$ after a time span equal to the projected recovery time ($T_{100\%}$).

In each subsequent year t, total current biomass B_t was calculated for both models as the sum of biomass on all 100 tracts, both fished and unfished. Catch in year t was equal to μB_t, and fishing was continued in this way until a new equilibrium was reached.

These two models were used to explore the relationship between recovery time, harvest rate, and biomass. First, the mean recovery time ($T_{100\%}$) for all tracts and the current annual harvest rate ($\mu = 0.027$) were used as input, and each model was run until B_t reached a stable fishing equilibrium (i.e., when $B_t = B_{t-1}$). The ratio of equilibrium biomass to unfished biomass (B_t / B_0) could then be compared to yield model predictions under the current $F_{40\%}$ management strategy ($B_t / B_0 = 0.40$). Second, the two models were used to search (using different trial values of μ) for the harvest rate μ which produced a fishing equilibrium corresponding to the current management target ($F_{40\%}$).

RESULTS

The average geoduck density (number/900 ft^2 transect) decreased following fishing at all 15 study tracts, then increased during the recovery (i.e., no-fishing) period (Table 1). The decrease following fishing averaged 72% and ranged from a low of 19% to a high of 95% (Table 2). Students t-tests showed that 14 of the 15 decreases were statistically significant (Table 3). At Agate Pass, the first post-fishing survey did not indicate a statistically-significant decrease compared to the pre-fishing survey. In other words, our surveys were not able to demonstrate any effect of fishing at Agate Pass. At five of the tracts, the increases in density between the first and second post-fishing surveys were not statistically significant (Table 3). Reported catches at each of the 15 tracts are given in Table 4.

The average estimated time to recover to pre-fishing density assuming complete removal of all geoducks ($T_{100\%}$) was 41.56 yr when data from all 15 tracts were included (Table 2). When the analysis was restricted to only those tracts with significantly different means (n = 9), the mean recovery time was 39.39 yr, ranging from a low of 11 yr at Indian Island to a high of 73 yr at Dougall Point 2 (Table 2).

Using mean $T_{100\%}$ = 39 yr, the optimum constant-catch harvest rate was equal to 1 / (39+1) = 0.025 (Eq. 4). Thus, under the assumption of constant recovery rate and an average 39-yr "turnover time" for tracts, an annual harvest rate of $2.5\% B_0$ is expected to be the maximum which would allow for continuous rotation of tracts. During the years when Washington managers used a constant-catch strategy, an annual harvest rate of $2\% B_0$ was in effect.

With mean $T_{100\%}$ = 39 yr, the proportion of biomass being replaced each year for the linear model was equal to $1/T_{100\%}$ = 0.0256. Thus, a tract originally containing 100 units of biomass would recover 2.56 units each year following harvest, recovering all 100 units 39 years after fishing. Using this value in the linear model resulted in a fishing equilibrium at $B_t / B_0 = 0.65$ following 47 yr of fishing at the current harvest rate $\mu = 0.027$ (Figure 2). Thus, the linear model when applied to recovery study data suggests that an annual harvest rate of 2.7% will eventually reduce spawning biomass to 65% of its unfished level, rather than the 40% predicted by the equilibrium yield model and $F_{40\%}$ strategy. Figure 2 shows, however, that prior to reaching equilibrium, biomass dipped to $B_t / B_0 = 0.63$ at 34 yr.

For the logistic model, the intrinsic rate of population growth (r) which allowed complete recovery of tract biomass after 39 yr was found by iteration to be 0.2675 (Figure 3). The biomass trajectory using the logistic model was similar to those predicted by the linear model (Figure 2), but biomass dipped to $B_t / B_0 = 0.62$ at 24 yr before reaching equilibrium at $B_t / B_0 =$ 0.64 in 49 yr.

We next searched for the harvest rate which, assuming an average recovery time of 39 yr, reduced B_t / B_0 to no less than 0.40. Because the logistic model always allowed biomass to dip below the predictions of the linear model, only the logistic model was used in this analysis. The annual harvest rate which dropped B_t / B_0 to 0.40 (i.e., corresponding to the $F_{40\%}$ strategy) was 0.057, or $5.7\% B_t$ (Figure 4). This harvest rate eventually produced a long-term fishing equilibrium at $B_t / B_0 = 0.45$ after 48 yr (Figure 4).

DISCUSSION

The preliminary results of this study confirm that post-fishing recruitment does occur on commercial geoduck tracts. The preliminary results also confirm earlier hypotheses (Goodwin and Shaul 1984) that recruitment (and consequently the time required for recovery) varies considerably from tract to tract. Thus, under the rotational harvest strategy, certain tracts are expected to be re-harvested more often than others. Under such a management strategy, the optimum sustainable harvest rate is one which corresponds with the average recovery time in a management region. Based on these preliminary post-fishing data, the average recovery time is 39 yr, suggesting that model-based harvest rates (both the former constant-catch $2\%B_0$ and the current constant harvest rate $2.7\%B_t$) are somewhat conservative (i.e., sub-optimal). It is noteworthy, however, that harvest rates based on recovery time fall short of model-based harvest rates which are predicted to maximize yield-per-recruit ($7.5\%B_t$; Bradbury and Tagart 2000; Bradbury *et al.* 1997). One possible reason is that commercial fishing may adversely affect recruitment, a hypothesis which agrees with the earlier experimental results of Goodwin and Shaul (1984).

The recovery data presented here should be considered preliminary, for the obvious reason that recovery times have been projected from just two post-fishing data points, both fairly early in the recovery of most tracts.

We recommend that the recovery study be continued in the future. Additional post-fishing data points at all tracts will more reliably define both the form and the time required for recovery. Additional surveys may also require some adjustment in the underlying assumption of a population at long-term equilibrium. There is some indication in the preliminary results that density on some tracts (e.g., Fern Cove) may increase to a level above the pre-fishing density. Conversely, it is also possible that some tracts may fail to reach pre-fishing densities, perhaps due to niche-filling by other organisms following the geoduck fishery (e.g., horse clams).

Managers should also consider expanding the recovery study in the future to include other fished tracts. One of the problems in extrapolating results of the present study is that the study tracts were selected neither randomly or systematically. This resulted in "clumping" of study tracts in some areas, and the absence of study tracts in other areas. From a practical standpoint it is impossible to select sites randomly or systematically, but some attempt could be made to expand the number of study tracts and fill in geographic gaps wherever possible. Additional study tracts would increase the reliability of the study, and possibly allow for the analysis of spatial patterns in recovery.

The recovery study should continue to serve as an independent, empirical test of predictions based on structural models of the geoduck population. Empirical models of this sort rely on fewer assumptions than structural models, and their predictions reflect the net effects of *all* the variables which may affect a population. These include natural environmental and climactic changes, competition with other species, the stock-recruitment relationship, even poaching and pollution. Empirical models do not imply causality, and therefore do not shed light on the underlying biological processes affecting populations. But as Fogarty (1989) points out, it is often possible to make more accurate predictions with empirical models than with structural models. As more data are gathered on the recovery tracts, managers may choose to replace yield-model harvest rates with empirically-based harvest rates. For the moment, however, structural and empirical models of the geoduck population are likely to play complementary roles in fisheries management.

Acknowledgements

The authors would like to thank Bob Sizemore, Don Rothaus, Amy Leitman, and the late Dwight Herren for their participation in post-harvest dive surveys. Dwight Herren performed the statistical tests, and Michael Ulrich created the site map. Don Flora and Dr. José (Lobo) Orensanz contributed their considerable modeling and biological expertise, and critiqued earlier drafts.

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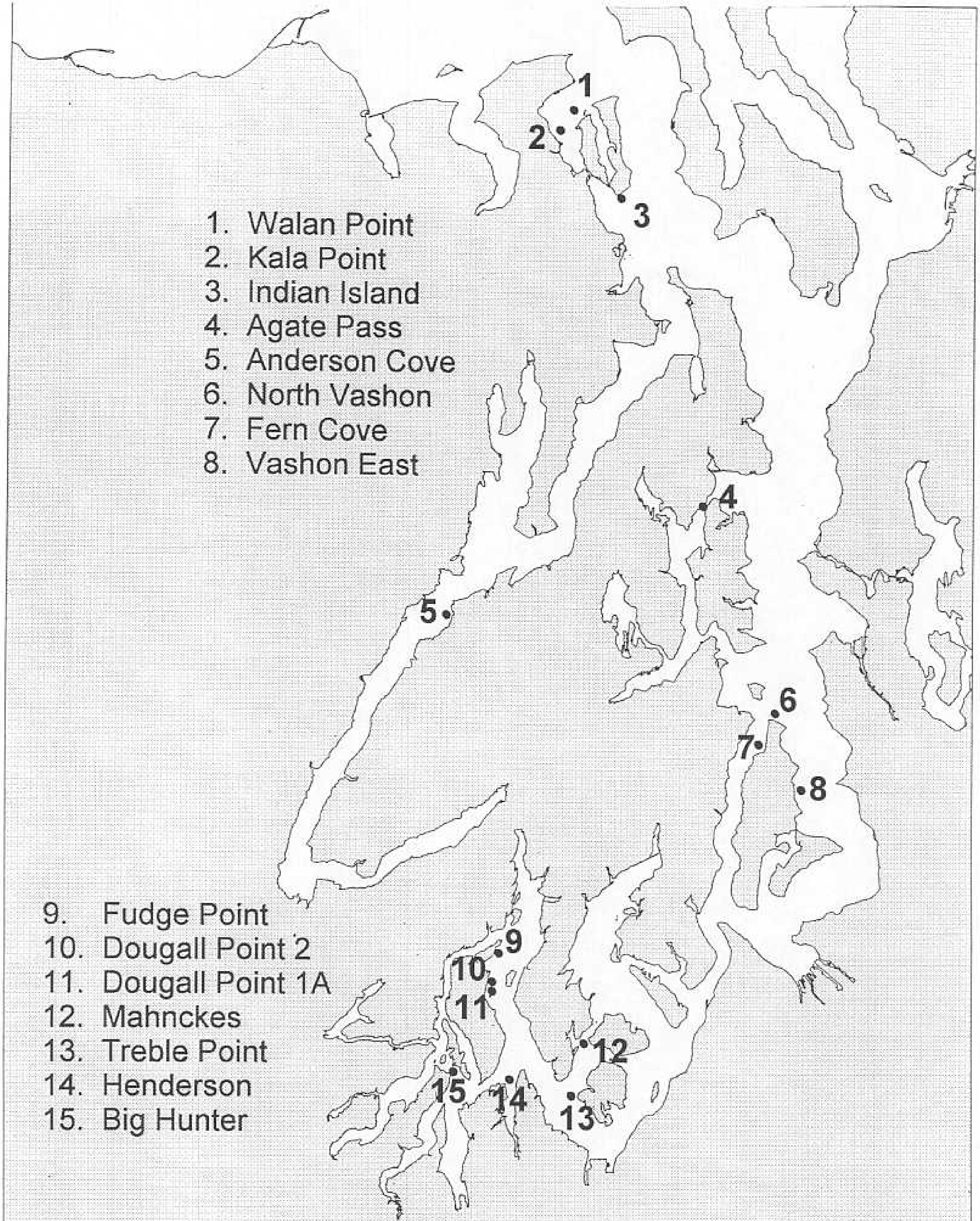
Revised: August 29, 2000

Figure 1. Commercial geoduck tracts surveyed in the recovery study.



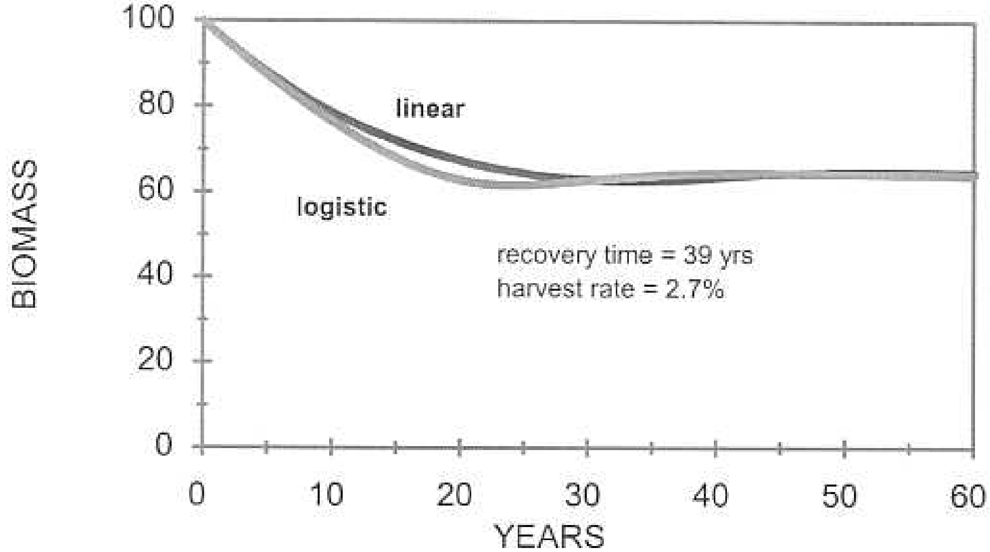


Figure 2. The effect of a constant harvest rate strategy ($\mu = 0.027$) on geoduck biomass, assuming an average recovery time to pre-fishing density on individual tracts of 39 yr. Predictions were calculated using linear and logistic recovery models described in the text.

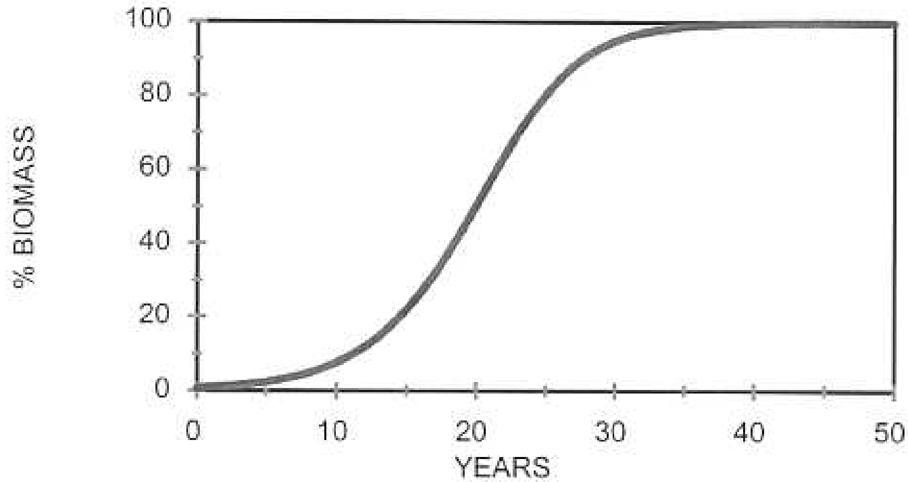


Figure 3. The logistic recovery model for an individual geoduck tract assuming a mean recovery time of 39 yrs for biomass to recover to its unfished level. The logistic parameters for the curve are $r = 0.2675$ and $K = 100$.

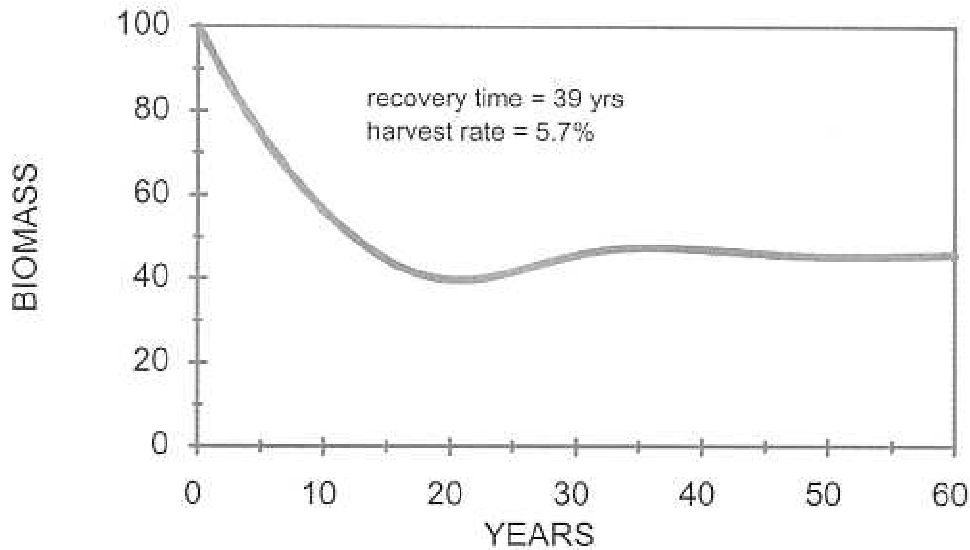


Figure 4. The effect of a constant harvest rate strategy ($\mu = 0.057$) on geoduck biomass, assuming an average recovery time to pre-fishing density on individual tracts of 39 yr. Predictions were calculated using the logistic recovery model described in the text.

Table 1 (continued). Geoduck survey data.

Tract name: Anderson Cove

Station	Geoduck Density (number/900 square feet)		
	Prefishing May 21-22,1985	1st Postfishing October 3-4,1988	2nd Postfishing June 15,1992
1	38	1	12
2	14	4	0
10	16	5	17
17	112	5	20
18	88	3	8
19	48	4	10
25	57	3	7
26	50	1	13
27	26	1	29
28	37	7	18
29	18	9	17
35	76	5	12
36	35	3	6
Mean	47.31	3.92	13.00
n	13	13	13
s.d.	29.60	2.36	7.37
CV	0.63	0.60	0.57

Table 1 (continued). Geoduck survey data.

Tract name: Henderson

Station	Geoduck Density (number/900 square feet)		
	Prefishing May 1-29,1984	1st Postfishing July 21-22,1986	2nd Postfishing July 1-15,1992
12	100	33	21
13	149	27	29
14	143	74	84
16	87	111	177
17	185	80	58
18	56	115	38
19	141	56	44
20	190	59	56
21	159	24	61
22	230	32	72
23	118	13	65
24	39	10	43
31	121	60	70
32	110	44	81
33	143	33	94
34	199	82	59
35	282	91	108
36	318	32	9
64	182	68	122
65	151	57	63
68	131	21	81
69	47	5	99
102	117	6	46
103	73	107	50
104	166	90	26
105	242	11	79
106	286	73	179
107	339	158	85
108	211	120	169
114	314	80	29
115	189	54	45
117	195	121	69
118	63	21	24
Mean	165.94	59.64	70.76
n	33	33	33
s.d.	79.83	39.59	42.43
CV	0.48	0.66	0.60

Table 1 (continued). Geoduck survey data.

Tract name: Fern Cove

Station	Geoduck Density (number/900 square feet) Prefishing May 9-18,1983	1st Postfishing July 18-19,1985	2nd Postfishing June 18-25,1992
1	133	315	141
2	126	53	48
4	237	16	62
7	81	6	10
8	23	131	181
12	158	94	179
15	141	106	232
16	42	8	13
17	162	108	221
20	43	6	5
21	182	80	145
22	194	206	288
26	31	40	20
27	162	121	29
28	162	297	67
29	20	13	29
30	72	15	33
31	105	104	26
32	176	167	126
33	163	208	397
39	3	6	1
40	6	13	3
41	8	13	3
42	12	13	16
43	40	108	23
53	196	138	439
54	148	46	261
55	73	13	221
56	31	7	100
61	69	5	14
62	83	13	31
63	146	113	122
67	146	5	152
68	237	37	229
73	77	147	14
74	232	388	307
Mean	108.89	87.75	116.33
n	36	36	36
s.d.	72.05	97.08	119.39
CV	0.66	1.11	1.03

Table 1 (continued). Geoduck survey data.

Tract name: Walan Point

Station	Geoduck Density (number/900 square feet)		
	Prefishing June 3-4,1985	1st Postfishing Sept. 20,1988	2nd Postfishing Sept. 1,1993
1	93	8	31
2	48	4	6
7	44	10	16
8	80	5	24
9	94	7	14
10	70	13	13
11	91	12	3
12	29	7	6
13	35	11	10
14	37	9	14
32	27	7	11
33	28	2	6
34	17	4	6
35	17	7	10
36	32	5	13
37	26	2	9
38	17	3	11
39	49	1	13
40	42	0	27
41	66	1	12
42	47	2	4
43	31	12	3
44	45	14	4
45	22	7	7
Mean	45.29	6.38	11.38
n	24	24	24
s.d.	24.49	4.14	7.30
CV	0.54	0.65	0.64

Table 1 (continued). Geoduck survey data.

Tract name: Vashon East

Station	Geoduck Density (number/900 square feet) Prefishing *April 19,1983 **June 6,1979	1st Postfishing July 22-23,1985	2nd Postfishing Sept 14-16,1993
5*	277	36	84
7*	193	12	68
9*	226	20	58
11*	241	17	86
12*	199	9	94
13**	116	14	75
14*	158	6	44
15*	175	12	102
16*	183	8	32
17*	218	9	68
18*	114	3	23
19*	187	16	23
20*	125	7	14
21*	188	7	25
22*	82	27	31
23*	197	16	47
25*	110	14	54
26*	158	53	116
29*	112	24	87
30*	83	38	150
31*	108	32	55
33*	96	15	151
34**	77	41	24
36*	55	118	63
38*	179	55	87
39*	154	64	219
41**	51	77	202
44*	105	46	139
45*	111	44	228
Mean	147.52	28.97	84.45
n	29	29	29
s.d.	58.01	25.86	59.03
CV	0.39	0.89	0.70

Table 1 (continued). Geoduck survey data.

Tract name: Mahnckes

Station	Geoduck Density (number/900 square feet) Prefishing June 6,1983	1st Postfishing July 10,1985	2nd Postfishing May 3,1993
7	187	20	84
8	131	18	44
9	159	30	127
10	220	25	97
11	184	35	79
12	136	30	107
13	158	30	139
14	199	39	71
15	213	23	145
16	175	59	77
17	135	16	83
18	223	46	240
19	84	5	41
20	177	46	134
21	221	67	128
22	274	64	117
25	201	115	151
26	238	96	185
30	123	245	238
31	142	6	0
32	108	191	187
33	116	134	228
34	127	19	257
35	16	0	364
38	84	36	248
39	123	87	99
42	47	31	25
43	36	40	49
Mean	151.32	55.46	133.71
n	28	28	28
s.d.	63.06	56.60	84.02
CV	0.42	1.02	0.63

Table 1 (continued). Geoduck survey data.

Tract name: Dougall Point 1A

Station	Geoduck Density (number/900 square feet)		
	Prefishing April 3,1984	1st Postfishing July 10,1986	2nd Postfishing July 11-12,1994
1	74	57	61
2	90	17	46
3	125	13	34
4	158	16	43
5	19	4	28
6	238	3	19
7	277	3	38
8	40	21	23
10	165	8	20
11	40	17	20
12	175	4	12
13	120	7	19
14	47	14	15
15	91	10	24
Mean	118.50	13.86	28.71
n	14	14	14
s.d.	77.09	13.77	13.93
CV	0.65	0.99	0.49

Table 1 (continued). Geoduck survey data.

Tract name: Fudge Point

Station	Geoduck Density (number/900 square feet) Prefishing May 17-19,1982	1st Postfishing June 14,1984	2nd Postfishing July 12-22,1994
1	100	64	91
2	46	49	81
4	127	7	17
5	119	34	57
6	74	26	27
7	88	43	37
8	131	61	26
9	71	3	21
10	91	8	10
11	128	22	17
12	134	20	14
13	120	30	21
14	29	10	10
15	92	8	6
16	130	21	38
17	113	34	118
18	134	84	102
24	33	4	21
25	81	10	20
26	142	11	11
27	176	13	50
28	156	33	65
Mean	105.23	27.05	39.09
n	22	22	22
s.d.	38.61	21.85	32.80
CV	0.37	0.81	0.84

Table 2. Projected recovery time of fished geoduck tracts to pre-fishing density:

GEODUCK TRACT	MEAN GEODUCK DENSITY (no./900 square ft) prefishing	first postfishing	second postfishing	% decrease i density due to fishing	increase in postfishing density (no./900 sq ft	years of recovery	recruitment (no./sq ft/yr)	PROJECTED RECOVERY TIME (YRS) partial recovery	recovery after 100% catch
Indian Island/Kinney Point	94.36	14.18	61.45	84.97	47.27	5.68	0.009	9.63	11.34
Big Hunter	116.06	12.75	44.00	89.01	31.25	10.80	0.003	35.70	40.11
Kala Point	68.25	3.25	9.20	95.24	5.95	5.65	0.001	61.69	64.77
North Vashon	102.63	60.79	121.33	40.76	60.54	7.90	0.009	5.46	13.40 *
Treble Point	283.43	125.86	194.86	55.59	69.00	7.84	0.010	17.91	32.22 *
Agate Pass	79.76	28.71	73.29	64.00	44.57	10.98	0.005	12.57	19.64 **
Anderson Cove	47.31	3.92	13.00	91.71	9.08	3.70	0.003	17.69	19.29
Henderson	165.94	59.64	70.76	64.06	11.12	5.97	0.002	57.06	89.08 *
Fern Cove	108.89	87.75	116.33	19.41	28.58	6.93	0.005	5.13	26.42 *
Walan Point	45.29	6.38	11.38	85.92	5.00	4.95	0.001	38.53	44.84
Mahnckes	151.32	55.46	133.71	63.35	78.25	7.82	0.011	9.58	15.12
Vashon East	147.52	28.97	84.45	80.36	55.48	8.16	0.008	17.43	21.69
Fudge Point	105.23	27.05	39.09	74.30	12.05	10.10	0.001	65.53	88.20 *
Dougall Point 1A	118.50	13.86	28.71	88.31	14.86	8.01	0.002	56.40	63.87
Dougall Point 2	142.13	25.88	45.38	81.79	19.50	10.08	0.002	60.09	73.46
Minimum	45.29	3.25	9.20	19.41	5.00	3.70	0.001	5.13	11.34
Maximum	283.43	125.86	194.86	95.24	78.25	10.98	0.011	65.53	89.08
Mean	118.44	36.96	69.80	71.92	32.83	7.64	0.005	31.36	41.56
STD	58.24	34.91	52.81	21.09	24.62	2.20	0.004	23.13	27.51
CV (std/mean)	0.49	0.94	0.76	0.29	0.75	0.29	0.742	0.74	0.66
Restricting analysis to beds with significantly different means:									
Minimum									11.34
Maximum									73.46
Mean									39.39
STD									23.79
CV (std/mean)									0.60

* no statistically significant difference between mean first and mean second postfishing densities

** no statistically significant difference between mean pre-fishing and mean first postfishing densities

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Table 2. Projected recovery time of fished geoduck tracts to pre-fishing density:

GEODUCK TRACT	MEAN GEODUCK DENSITY (no./900 square ft) prefishing	first postfishing	second postfishing	% decrease i density due to fishing	increase in postfishing density (no./900 sq ft	years of recovery	recruitment (no./sq ft/yr)	PROJECTED RECOVERY TIME (YRS) partial recovery	recovery after 100% catch
Indian Island/Kinney Point	94.36	14.18	61.45	84.97	47.27	5.68	0.009	9.63	11.34
Big Hunter	116.06	12.75	44.00	89.01	31.25	10.80	0.003	35.70	40.11
Kala Point	68.25	3.25	9.20	95.24	5.95	5.65	0.001	61.69	64.77
North Vashon	102.63	60.79	121.33	40.76	60.54	7.90	0.009	5.46	13.40 *
Treble Point	283.43	125.86	194.86	55.59	69.00	7.84	0.010	17.91	32.22 *
Agate Pass	79.76	28.71	73.29	64.00	44.57	10.98	0.005	12.57	19.64 **
Anderson Cove	47.31	3.92	13.00	91.71	9.08	3.70	0.003	17.69	19.29
Henderson	165.94	59.64	70.76	64.06	11.12	5.97	0.002	57.06	89.08 *
Fern Cove	108.89	87.75	116.33	19.41	28.58	6.93	0.005	5.13	26.42 *
Walan Point	45.29	6.38	11.38	85.92	5.00	4.95	0.001	38.53	44.84
Mahnckes	151.32	55.46	133.71	63.35	78.25	7.82	0.011	9.58	15.12
Vashon East	147.52	28.97	84.45	80.36	55.48	8.16	0.008	17.43	21.69
Fudge Point	105.23	27.05	39.09	74.30	12.05	10.10	0.001	65.53	88.20 *
Dougall Point 1A	118.50	13.86	28.71	88.31	14.86	8.01	0.002	56.40	63.87
Dougall Point 2	142.13	25.88	45.38	81.79	19.50	10.08	0.002	60.09	73.46
Minimum	45.29	3.25	9.20	19.41	5.00	3.70	0.001	5.13	11.34
Maximum	283.43	125.86	194.86	95.24	78.25	10.98	0.011	65.53	89.08
Mean	118.44	36.96	69.80	71.92	32.83	7.64	0.005	31.36	41.56
STD	58.24	34.91	52.81	21.09	24.62	2.20	0.004	23.13	27.51
CV (std/mean)	0.49	0.94	0.76	0.29	0.75	0.29	0.742	0.74	0.66

Restricting analysis to beds with significantly different means:	
Minimum	11.34
Maximum	73.46
Mean	39.39
STD	23.79
CV (std/mean)	0.60

* no statistically significant difference between mean first and mean second postfishing densities

** no statistically significant difference between mean pre-fishing and mean first postfishing densities

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Table 3. Results of the student's t-test (with unequal variance) comparing mean densities on fish
Geoduck densities were log-transformed prior to performing the t-tests.

GEODUCK TRACT	PREFISHING MEAN DENSITY V 1ST POSTFISHING MEAN DENS			1ST POSTFISHING MEAN DENSI 2ND POSTFISHING MEAN DEN		
	reject null H	t-value	t critical (one-tail)	reject null H	t-value	t critical (one-tail)
Indian Island/Kinney Poi	yes	6.45	1.68	yes	-4.08	1.68
Big Hunter	yes	2.37	1.72	yes	-2.78	1.70
Kala Point	yes	10.93	1.69	yes	-2.43	1.70
North Vashon	yes	2.04	1.68	no	-1.45	1.68
Treble Point	yes	3.58	1.73	no	-1.31	1.71
Agate Pass	no	0.91	1.69	yes	-2.67	1.68
Anderson Cove	yes	9.79	1.71	yes	-3.47	1.72
Henderson	yes	6.60	1.67	no	-1.51	1.67
Fern Cove	yes	1.96	1.67	no	-0.75	1.67
Walan Point	yes	10.59	1.68	yes	-3.03	1.68
Mahnckes	yes	5.52	1.68	yes	-3.47	1.67
Vashon East	yes	10.66	1.68	yes	-5.58	1.67
Fudge Point	yes	7.53	1.69	no	-1.46	1.68
Dougall Point 1A	yes	7.46	1.71	yes	-3.76	1.72
Dougall Point 2	yes	4.30	1.78	yes	-1.93	1.80

yes = reject the null hypothesis that the two mean densities are equal.

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Table 4. Geoduck harvest at 15 fished tracts between the prefishing survey and first postfishing survey.

Tract name	Tract siz (acres)	Catch (number of geoducks rounded to nearest 1,000)
Indian Island/Kinney Point	76	361,000
Big Hunter	93	951,000
Kala Point	65	270,000
North Vashon	36	441,000
Treble Point	15	259,000
Agate Pass	156	3,625,000
Anderson Cove	65	96,000
Henderson	59	714,000
Fern Cove	116	472,000
Walan Point	152	353,000
Mahnckes	73	201,000
Vashon East	53	395,000
Fudge Point	70	574,000
Dougall Point 1A	26	351,000
Dougall Point 2	20	349,000

Stock Assessment of Subtidal Geoduck Clams (*Panopea abrupta*) in Washington

by

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Bob Sizemore
Don Rothaus
Michael Ulrich

Marine Resources Unit
Fish Management Division
Fish Program

January 2000

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Glossary

Annual mortality rate (A) - The number of animals which die during a year divided by the initial number.

Constant *F* strategy - A harvest strategy which sets the annual quota as a function of current population size and a recommended instantaneous fishing mortality rate.

CV - Coefficient of variation, a relative measure of statistical precision (the standard error of an estimator divided by the estimator, and expressed as a percentage).

DGPS - Differential Global Positioning System, a satellite navigational system which uses a shore-based slave station to provide extremely accurate position fixes on the surface of the earth.

DNR - Washington Department of Natural Resources.

Dig sample - A sample of geoducks (generally ten) dug with commercial water jet gear within a previously surveyed 900 ft^2 transect on a geoduck tract, used in estimating mean weight per geoduck.

Dimple - A visible depression or "show" caused by a geoduck or other clam siphon which is partially retracted in the substrate.

Equilibrium yield - The yield in weight taken from a stock when it is in equilibrium with fishing of a given intensity.

Exploitation rate (μ) - The fraction of the initial population removed fishing in one year; equivalent to the product of the annual mortality rate and the fishing mortality rate divided by the total mortality rate ($\mu = FA / Z$).

Fishing mortality rate (*F*) - The ratio of number of animals harvested per unit of time to the population abundance at that time, if all harvested animals were to be immediately replaced so that the population does not change (an instantaneous rate). The portion of total instantaneous mortality due to fishing.

Geoduck Atlas - An annual WDFW publication listing all known geoduck tracts in Washington, along with maps of their location, their commercial status, estimates of geoduck biomass, and other summary information.

Grid line - The primary sampling unit in geoduck surveys, along which a series of 900 ft^2 strip transects is aligned; usually run perpendicular to shore.

Harvestable geoducks - Geoducks of a size in which the siphon or "show" is likely to be seen by a diver; generally, geoducks with a total weight > 300 grams and >5 yrs old.

Harvest rate - Same as exploitation rate, see above.

Harvest strategy - A quantitative plan which states how catch will be adjusted from year to year, usually depending on the size of the stock.

MLLW(Mean Lower Low Water) - The arithmetic mean of the lower low water heights of a mixed tide observed over a specific 19-year Metonic cycle at a specific tidal reference station. Used to correct ambient depths (from diver depth gauges) to a standard tidal datum.

Natural mortality rate (*M*) - The ratio of number of animals which die from non-fishing causes per unit of time to the population abundance at that time, if all dead animals were to be immediately replaced so that the population does not change (an instantaneous rate). The portion of total instantaneous mortality due to natural (i.e., non-fishing) causes.

Rafeedie decision - The popular term for United States v. Washington No. 9213, subproceeding 89-3, a federal district court decision regarding treaty tribal rights to shellfish, including geoducks.

Show - When applied to geoducks, either a geoduck siphon visible above the substrate surface, or a depression or mark left in the substrate which can be identified as having been made by a geoduck.

Show factor - The ratio of geoduck shows visible during a single observation of any defined area to the true abundance of harvestable geoducks in that area.

Show plot - Permanently-marked subtidal areas in which the absolute number of harvestable geoducks is known from repeated tagging; show plots are used to estimate geoduck show factors.

SPR (Spawning Biomass Per Recruit) - The biomass of sexually mature members of a stock, expressed in terms of weight per recruit. Mathematically, the product of numbers-at-age, weight-at-age, and the proportion mature-at-age, summed over all ages in the population.

Stock-recruit (S-R) relationship - The functional relationship between the biomass (or number) of spawning stock and the resultant biomass (or number) of recruits.

Strip transect - See Transect below.

Subtidal geoduck - A geoduck living at a depth never uncovered by the tides (i.e., below the level of the extreme low spring tide at a given location).

TAC (Total Allowable Catch) - The number or weight of fish which may be harvested in a specific unit of time. As used in this report, the product of the estimated biomass of harvestable geoducks and the recommended annual harvest rate.

Total mortality rate (*Z*) - The ratio of number of animals which die from all causes per unit of time to the population abundance at that time, if all dead animals were to be immediately replaced so that the population does not change (an instantaneous rate).

Tract - A subtidal area with defined boundaries which contains geoducks. See *Definition of Key Terms* for a full discussion.

Transect - The secondary sampling unit for geoduck density. In this report, a standard strip transect 150 ft long by six ft wide (= 900 ft^2) within which divers count all geoducks which are "showing."

WDFW - Washington Department of Fish and Wildlife.

Abstract

WDFW is mandated to perform biological stock assessment of the commercial geoduck resource and to make annual recommendations on the Total Allowable Catch (TAC) for each geoduck management region. Systematically spaced strip transect surveys are used to estimate the density of harvestable geoducks within commercial tracts, and a sample of geoducks is taken from these transects to estimate average weight. Biomass estimates on commercial tracts are the product of mean biomass per unit area and the total area of the tract. Regional biomass estimates are the sum of all surveyed commercial tract estimates within the region. Regional TACs are the product of the regional biomass estimate and the recommended harvest rate. An age-based equilibrium yield model was used to predict the long-term consequences of various harvest rates, using geoduck life history parameters which were estimated from existing WDFW data and literature sources. The model predicts yield and spawning biomass per recruit over a range of fishing mortality rates. Five commonly-used constant harvest rate strategies were simulated with the model, including two based on yield-per-recruit analysis and three based on spawning biomass per recruit analysis. An $F_{40\%}$ strategy is recommended as a risk-averse policy for geoducks. Under an $F_{40\%}$ strategy, the recommended annual TAC is 2.7% of the current commercial biomass within a region.

Introduction

Geoduck clams (*Panopea abrupta*) dominate the biomass of benthic infaunal communities in many parts of Puget Sound. Goodwin and Pease (1989) summarized the biology and commercial dive fishery for geoducks, which began in 1970 in Washington state. Commercial fisheries also exist in British Columbia and Alaska (Campbell *et al.* 1998), and geoducks now provide the most valuable commercial clam harvest on the Pacific coast of North America. The average annual ex-vessel value of Washington's geoduck harvest from 1990-1998 was US$14 million. From 1971 through 1998, annual landings have averaged 3.3 million pounds.

The commercial geoduck fishery is jointly managed by two state agencies, Washington Department of Fish and Wildlife (WDFW) and the Department of Natural Resources (DNR), as well as the treaty Indian tribes with shellfishing rights affirmed by a 1994 federal district court judgement (the Rafeedie decision). WDFW's role is to perform biological stock assessment of the resource and to make recommendations on the Total Allowable Catch (TAC) which is expected to maintain a stable long-term commercial fishery.

WDFW began SCUBA diving surveys of geoducks in 1967, and surveys have continued on a yearly basis since that time, with a number of improvements and modifications. Treaty Tribes under co-management with the state began geoduck surveys in 1996. A modified Ricker yield-per-recruit model was adopted in 1981 for use in setting the statewide TAC. This inital research was updated and adopted by state and Tribal managers in 1997 with an equilibrium yield model.

This report describes the methods currently used by WDFW and treaty Tribes to assess subtidal geoduck populations and make annual recommendations on the TAC.

Part I of this paper describes the procedures used to estimate the biomass of harvestable geoducks on subtidal tracts of land. Part II describes the simulation of various harvest rate strategies via equilibrium yield modeling, and recommends a harvest rate based on this modeling to be used in the calculation of the TAC.

Goals and Objectives of Geoduck Stock Assessment

The long-term goal of geoduck stock assessment is to provide managers with the biological information needed to recommend a Total Allowable Catch (TAC). Currently, managers recommend separate TACs for each of six geoduck management regions, the boundaries of which are shown in Figure 1.

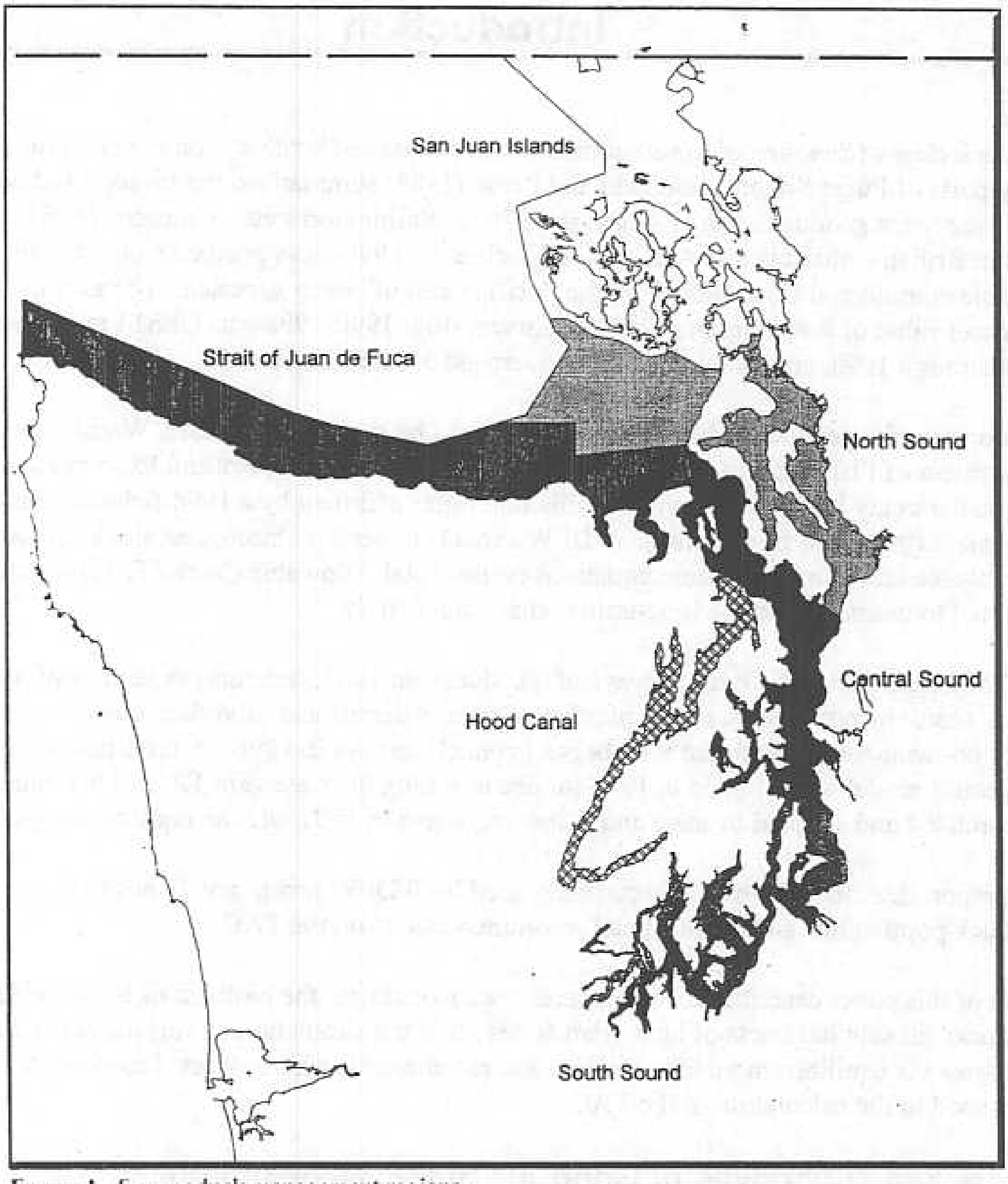


Figure 1. Six geoduck management regions.

The TAC for a given management region is the product of the current estimate of harvestable biomass of geoducks in the region and the recommended harvest rate for the region. Thus, the two short-term goals of geoduck stock assessment are: 1) To estimate harvestable geoduck biomass in each region, and: 2) To recommend a biologically sustainable harvest rate.

In order to reach the first of these short-term goals -- an estimation of harvestable biomass in each region -- dive surveys are carried out each year on relatively small subtidal areas known as "tracts." The objective of such surveys is to estimate the biomass of harvestable geoducks within the confines of the tract. The sum of biomass estimates on all commercial tracts surveyed within a region comprises the regional biomass estimate. Since only a few tracts can be surveyed each year, regional biomass estimates consist of the most recent estimate for each surveyed tract in the region, with known commercial catches subtracted from those tracts which are fished. Biomass estimates for all surveyed tracts are summarized yearly in the annual Geoduck Atlas. The Atlas is published by WDFW in collaboration with the treaty Tribes and is available from the Point Whitney Shellfish Laboratory. Part I of this paper describes the current procedures for making biomass estimates.

In order to reach the second short-term goal -- recommendation of an annual harvest rate -- estimates of important geoduck life history parameters were used to drive an age-based equilibrium yield model. The objective of this yield modeling was to predict the long-term effect of various harvest rates on equilibrium yield and spawning biomass per recruit, and to recommend one of these harvest rates for use in computing regional TACs. Part II of this paper describes the yield modeling and the rationale for recommending a particular harvest rate.

Figure 2 is a flow chart which shows these steps leading to regional TAC recommendations.

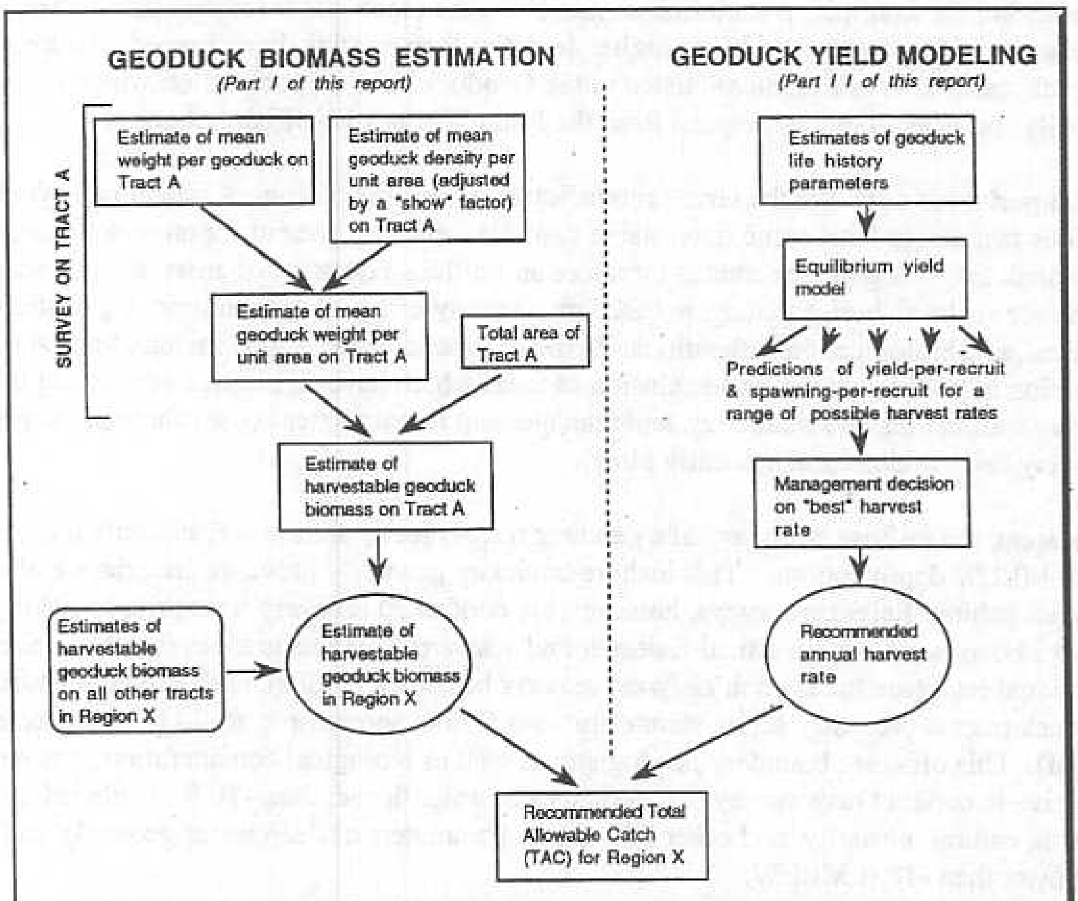


Figure 2. Steps leading to a geoduck biomass estimate on Tract "A" and an annual TAC recommendation for Management Region "X."

Definition of Key Terms

Three key terms -- geoduck tract, geoduck bed, and harvestable geoducks -- are used extensively throughout this paper. All three deserve a thorough definition because they are frequently a source of confusion for biologists, managers, and the public.

Geoduck Tract

A geoduck tract is any subtidal area with well-defined boundaries which contains geoducks. Boundary lines are typically referred to as inshore, offshore, and side boundaries. ***Commercial tracts*** are those tracts in which geoduck densities are considered high enough to support a fishery and which have no other drawbacks to fishing (e.g., pollution, narrow width, land-use conflicts, poor quality geoducks, difficult digging conditions, conflicts with threatened or endangered species or their habitats, etc.). ***Non-commercial tracts*** are those tracts which cannot be fished for one or more reasons, including those listed above. The status of a tract is always subject to change; for example, commercial tracts may become non-commercial if they become polluted, or if they are fished out following a commercial harvest; non-commercial tracts may become commercial, for example, if pollution abates, if the area recovers from past fishing, market prices increase, or if new surveys indicate higher densities than previously estimated. All known geoduck tracts in Washington are listed in the Geoduck Atlas, a publication which is updated annually and is available on request from the Point Whitney Shellfish Laboratory.

It is important to note that the term "geoduck tract" has little biological meaning, beyond the obvious fact that at least some harvestable geoducks must be present for an area to be considered a geoduck tract. A geoduck tract is therefore an artificial construct of areas, the boundaries of which are set by fisheries managers based on a variety of logistic, economic, legal, social, political, and biological considerations. Some of these considerations include harvest control, exclusion of polluted areas, and exclusion of areas which have significant conflicting uses such as ferry traffic, marine sanctuaries, and management research areas (e.g., show plots, geoduck recovery beds, and natural mortality plots).

At present, the inshore boundary of a geoduck tract is set by statute and state/tribal agreements at -18 ft MLLW depth contour. This inshore boundary generally prevents disturbance of sensitive eelgrass habitat. Eelgrass surveys, however, are conducted on every tract prior to fishing, and the inshore boundary is set 2 vertical ft deeper and seaward where eelgrass is found to occur on an individual tract (see the section *Eelgrass surveys* below for details). The offshore boundary of a geoduck tract is presently set by statute and state/Tribal agreements at -70 ft (uncorrected for tide height). This offshore boundary is a logistic as well as biological consideration; it is not cost-effective to conduct dive surveys of geoducks in water deeper than -70 ft. Little is known about growth, natural mortality, and other life-history parameters of deep water geoducks and geoducks shallower than -18 ft MLLW.

Although the inshore and offshore boundaries of what is currently considered a geoduck tract are strictly defined by statute and state/tribal agreements as noted above, the side boundaries of a tract are flexible. Side boundaries should enclose areas which have adequate survey information, and therefore may never lie more than 500 feet from the nearest grid line of transects (see *Variations on the standard grid line layout* below). Subtidal geoducks may be found along the entire shoreline of Puget Sound, albeit at very low densities in some areas. Thus, there is no specific point along the shoreline at which any tract can be said to "end" because geoducks are no longer present. In some cases, managers fix the "end" of a tract at the point along the shore where geoduck density falls below the current standard for commercial density. This is an arbitrary economic standard, however, which is subject to change with market prices. Virtually all commercial geoduck tracts contain areas within which density falls below the commercial level.

Besides the density of geoducks, other considerations in setting the side boundaries of tracts include: navigational channels, ferry lanes, steeply sloping bottom contours which "pinch" the tract to a width which makes commercial fishing impractical, and prohibited areas classified as such by the Washington Department of Health. Some tracts in the current Geoduck Atlas end simply at the point where biologists ran out of time during the survey season to continue surveys along the shoreline.

The side boundaries of a tract may be set before performing surveys, during the survey, or afterwards. In any case, the final side boundaries of a surveyed tract are usually modified based on survey findings. For example, survey transects may fall within areas which are later found to be polluted or near navigational hazards, and these transect data may later be eliminated from the tract. It is usually easier and more cost-effective to throw out survey data from small portions of a tract than to return to the field and perform additional surveys.

Because tract boundaries are set at the convenience of fisheries managers, there is, in theory at least, no limit on the size of a geoduck tract. There are, however, practical limits. The management and survey costs per acre increase dramatically as tracts become smaller, making very small tracts uneconomical to lease. The smallest tract listed in the 2000 Geoduck Atlas is four acres, and the smallest tract ever commercially fished was five acres (Cooper Point). Extremely large tracts generally contain so much geoduck biomass that they may be divided into smaller tracts which can be fished in accordance with annual TACs or harvest shares. Large tracts also present compliance and enforcement problems. For example, the largest tract listed in the 1997 Geoduck Atlas was 2,452 acres (Jamestown 1, Tract #00450). Based on recent surveys this tract was subsequently reconfigured, and in the 2000 Geoduck Atlas appears as a 331 acre tract. The largest commercial tract in the 2000 Geoduck Atlas is 723 acres (Battle Point North, Tract #07000). The mean size of all tracts listed in the 2000 Geoduck Atlas is 106 acres (n = 267 tracts).

Existing tract boundaries may change annually to fit management needs. Large tracts are frequently divided into smaller ones, and small adjacent tracts are often joined to form a single, larger tract. New surveys may increase the side boundaries of certain tracts which had been previously surveyed.

Geoduck Bed

A geoduck bed is an aggregation of geoduck clams in the marine environment. Geoducks will recruit to areas with suitable substrate (sand or sand/mud mixtures), adequate current, sufficient food, and few predators. Geoduck beds occur from the intertidal zone to deep subtidal areas. A geoduck tract is typically a subset of a geoduck bed.

Harvestable Geoducks

Harvestable geoducks are those of a size in which the siphon or "show" is likely to be seen by a diver. Virtually all geoducks visible to experienced divers are of a marketable size. Washington samples indicate that geoducks first enter the fishery at 300 g, a weight which is usually attained between five and seven years (see the sections on *Growth* and *Fishery selectivity* in Part II of this paper). WDFW geoduck transect counts and weight samples made using the procedures described in this paper are assumed to closely mimic this commercial pattern of selectivity. In support of this assumption, we note that only 2% of the 11,181 geoducks sampled by WDFW divers during surveys from 1973-1985 weighed less than 300 g (Goodwin and Pease 1987).

Obviously, geoducks which are too small to be seen by divers are neither harvested by fishers nor counted by WDFW surveyers. Therefore, the procedures described in this paper for estimating the biomass of *harvestable* geoducks necessarily underestimate *total* geoduck biomass, because most geoducks <300 grams or <4 yr old are not counted. The only method which has been used to effectively sample geoducks smaller than this size in a quantitative way is excavation with a venturi suction dredge (Goodwin and Shaul 1984). Venturi samples, while useful for recruitment research on a very small spatial scale, are far too laborious and costly for estimating geoduck densities over large areas.

Part I. Estimation of Harvestable Geoduck Biomass

Sample Design for Estimating Geoduck Biomass

The objective of geoduck surveys is to estimate the biomass of harvestable geoducks within a specific tract. Biomass per unit area within the tract is estimated as the product of mean density and mean weight per geoduck; total biomass on the tract is estimated as the product of biomass per unit area and total area. Strip transect surveys are first carried out to estimate mean density within the tract, and a sample of geoducks is later taken from a subsample of these transects to estimate mean weight per geoduck.

The sample or target population is therefore all harvestable geoducks within the tract boundary. The experimental or sampling unit for geoduck density is a 900 ft^2 strip transect. The estimator is the mean density (in numbers per ft^2) of harvestable geoducks, i.e., the mean density from all transects taken within the tract. The experimental or sampling unit for geoduck weight is a cluster sample of ten geoducks haphazardly dug with commercial gear from a transect. The estimator is the mean weight (in grams) of all geoducks sampled within the tract.

The subsections below present the sampling and statistical methods used to estimate mean density, mean weight per geoduck, total biomass, and the statistical precision of the total biomass estimate

Estimation of Mean Geoduck Density

The density of harvestable geoducks within a tract is estimated by a systematic sampling technique first developed in 1967 (Goodwin 1973; Goodwin and Pease 1991). A series of standard strip transects, each comprising an area six ft wide by 150 ft long (a total area of 900 ft^2) are taken along grid lines which run directly offshore from the -18 ft MLLW contour to the -70 ft contour (uncorrected). The grid lines (primary sampling units) begin at a randomly-selected starting point along the shoreline of the tract and are spaced systematically in both directions thereafter at 1,000 ft intervals. Transects (secondary sampling units) are then taken back-to-back along each grid line. Figure 3 shows the arrangement of systematic samples on a typical tract. The section *Geoduck Survey Methods* below describes in detail the procedures used in the field.

The density of geoducks observed by divers within an individual transect is always an underestimate of the actual density present within that transect (Goodwin 1973; Goodwin 1977). Geoduck siphons may be retracted below the surface of the substrate, cryptic at the surface of the substrate, or obscured from view of the diver. The number of geoducks "showing" (i.e., observable to divers) compared to the number of geoducks actually present in the substrate is a function of various environmental factors such as food availability, water temperature, substrate type, algae cover, turbidity, and currents (Goodwin 1977).

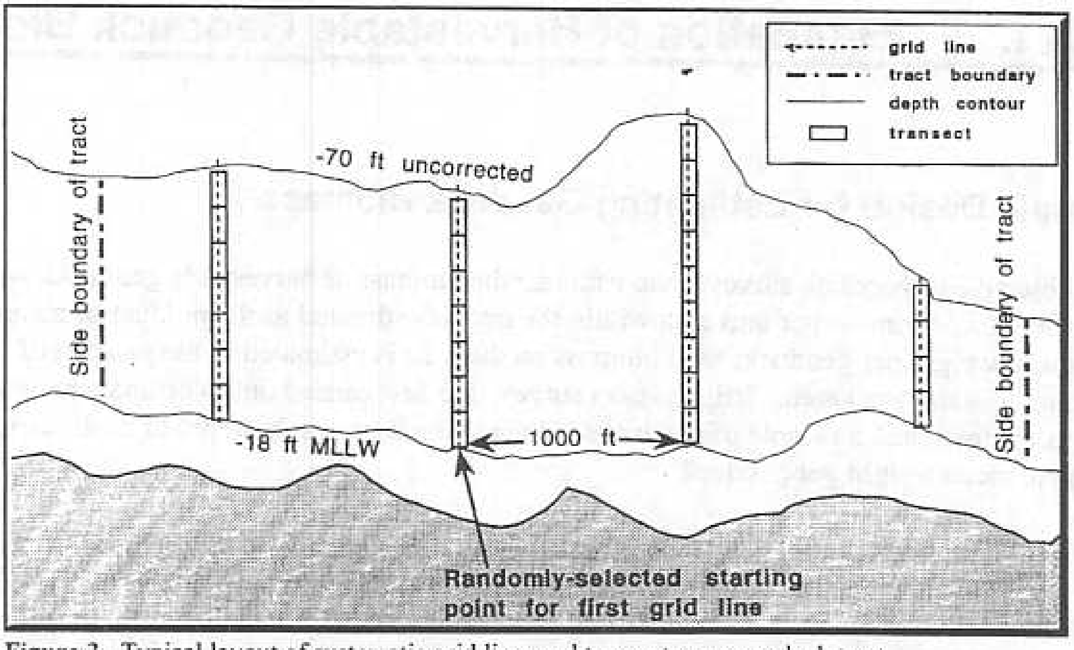


Figure 3. Typical layout of systematic grid lines and transects on a geoduck tract.

The estimate of geoduck density (number of geoducks per ft^2) for an individual transect is calculated by adjusting the observed density by a show factor as follows:

$$d_i = d_{obs}/S \quad (1)$$

where

d_i = density of geoducks (number per ft^2) on the *i*th transect

d_{obs} = density of geoducks (number per ft^2) observed by divers during a survey on the *i*th transect (for a 900 ft^2 transect, this is simply the total number of geoducks observed by both divers divided by 900). Note that the counts of both divers are summed to produce a single d_{obs} for each transect. Although it is tempting to consider each diver's count as a separate d_{obs} (therefore doubling the sample size), this would amount to "pseudoreplication" (Hurlbert 1984), because the two counts along the same 150-ft transect are obviously not independent.

S = "show factor" (within any defined area, the ratio of visible geoduck "shows" from a single observation and the true abundance of harvestable geoducks). A show factor of 0.75 is currently used to estimate density on all tracts for pre-fishing surveys unless there is a show plot established for a tract that will give site-specific data. Use of 0.75 as a constant show factor is a management decision that is assumed to give a conservative estimate of harvestable biomass. The section *Show plot surveys and show factors* below provides the basis for the 0.75 show factor, as well as detailed field procedures for establishing and counting a show plot.

The mean density of geoducks on a given tract is estimated as:

$$D = \Sigma d_i / n_D \qquad (2)$$

where

D = estimated mean density of geoducks

d_i = density of geoducks (number per ft^2) on the *i*th transect, adjusted by show factor as described above

n_D = sample n for density (number of transects surveyed)

The variance of the mean density (δ^2_D) is estimated as

$$\delta^2_D = \Sigma(d_i - D)^2 / n_D - 1 \qquad (3)$$

Estimation of Mean Weight per Geoduck

Following transect surveys, a series of cluster samples, each consisting of ten geoducks, are taken with commercial water jet harvest gear at systematically spaced intervals along each of the survey grid lines. Empirical studies suggest that reasonably precise and unbiased weight samples can usually be obtained by taking a cluster sample of ten geoducks systematically at one of every six to eight transects, beginning from a randomly selected transect (see the section *Sample size* below). This procedure ensures that all water depths are sampled, an important consideration because depth is a known biological gradient with respect to geoduck weight (Goodwin and Pease 1991). Because of the considerable set-up time involved in digging samples, cluster samples from a few systematically spaced transects are far more cost-effective than samples of individual geoducks from a large number of systematically or randomly chosen transects. The section *Geoduck dig (weight) samples* below provides detailed field and laboratory procedures for selecting dig stations, digging and processing the samples.

Mean weight per geoduck on a given tract is estimated as:

$$W = \Sigma w_i / n_W \qquad (4)$$

where

W = estimated mean weight per geoduck

w_i = weight of the *i*th geoduck from dig samples

n_W = sample n for weight

The variance of the mean weight per geoduck (δ^2_W) is estimated as:

$$\delta^2_W = \Sigma(w_i - W)^2/n_W - 1 \tag{5}$$

Estimation of Total Geoduck Biomass on the Tract

The estimate of total geoduck biomass on a tract is calculated as:

$$B_{tract} = (D)(W)(A) \tag{6}$$

where

B_{tract} = total geoduck biomass on a tract (in pounds)

D = estimated mean density of geoducks (number per ft^2, adjusted by a show factor as described above)

W = estimated mean weight per geoduck (in pounds)

A = total surface area of the tract (in ft^2) determined from GIS mapping software and tract maps prepared by DNR (see *Tract Mapping and Grid Line Placement Methods* below).

Precision of Geoduck Biomass Estimates

Statistical precision of the biomass estimate is reported in terms of the commonly-accepted 95% upper and lower confidence limits (i.e., $\alpha = 0.05$, two-tailed).

Confidence limits are calculated based on an estimate of the variance of the biomass (B), which is in turn the product of mean density and mean weight per geoduck. A standard variance-of-products formula (Goodman 1960) is used to calculate an unbiased estimate of this product. If geoduck density and weight per geoduck (i.e., D and W) are independently subject to sampling error (i.e., there is no correlation between density and weight), then the variance of B is given by:

$$\delta^2_B = D^2[\delta^2_W/n_W] + W^2[\delta^2_D/n_D] - [\delta^2_D\,\delta^2_W/n_D\,n_W] \tag{7}$$

where

δ^2_B = variance of B, estimated geoduck biomass per ft^2

D = mean density of geoducks (number per ft^2 adjusted by a show factor as described above)

W = mean weight (pounds per geoduck)

δ^2_D = variance of mean density

δ^2_W = variance of mean weight

n_D = sample n for mean density (number of transects)

n_W = sample n for mean weight (number of geoducks weighed)

The standard error (se) of *B* is calculated as the square root of δ^2_B.

The 95% confidence bound for a given geoduck tract of known size is given by:

$$B_{tract} \pm (t_{0.05,2,v})(se)(A) \tag{8}$$

where

B_{tract} = estimated geoduck biomass on an entire tract (in pounds)

$t_{0.05,2,v}$ = tabled t-value, $\alpha = 0.05$, two-tailed, v = df (degrees of freedom)

se = standard error of *B*

A = total area of tract (in ft^2)

For pre-harvest surveys on commercial beds, state and Tribal managers have agreed on a required precision for total biomass estimates of ±30% at the $\alpha = 0.05$ confidence level. In other words, the 95% confidence limit as calculated above must lie within ± 30% of the estimate of *B*.

Sample Size

The goal of pre-fishing surveys on an individual tract is to survey a sufficient number of transects and dig a sufficient number of geoducks to allow an unbiased estimate of geoduck biomass with 95% statistical confidence bounds which lie within ± 30% of the biomass estimate itself (see the section above). On the majority of tracts, the sample size required to meet these goals can be achieved by running a series of transects along grid lines placed systematically every 1,000 feet along the -18 ft MLLW contour, and digging a cluster sample of ten geoducks at every sixth to eighth transect. However, it is not always possible to achieve the required precision with this sampling scheme, particularly on narrow tracts, small tracts, or tracts with highly variable substrates. Two methods are used to roughly estimate the sample size (i.e., the number of transects) needed to meet the statistical precision requirements:

1. Prior to performing the survey, an empirically derived "rule of thumb" may be used in conjunction with the known surface area of the tract to roughly estimate the required number of transects. Evidence from past surveys on a variety of beds indicates that the sampling intensity listed in Table 1 usually meets or exceeds the required degree of statistical

precision. Note, however, that these are rough guidelines for pre-survey planning only, and in no way guarantee that biomass estimates will meet the precision requirements.

Table 1. Empirically derived guidelines for roughly estimating the sample size (number of transects) needed to meet statistical precision requirements on geoduck tracts of different sizes.

Size of tract (acres)	Number of 900 ft^2 transects per acre
1-5	3
6-15	2
16-50	1
51-100	0.66
100+	0.33

2. Once transect surveys have been completed along grid lines spaced every 1,000 feet along the -18 ft MLLW contour, it is possible to determine whether additional transects must be run based on the variance of transect counts already performed. Table 2 shows the coefficients of variation (CVs) for both mean geoduck density (*D*) and mean weight per geoduck *(W)* from 13 recently-surveyed tracts, and suggests that precision of the biomass estimate is almost totally dependent on the variance of density. Doubling the CV of density almost always produces a result within one or two percentage points of the precision of the biomass estimate. For example, doubling the CV of density on the Eld Inlet East tract results in 28.2%; after geoduck samples were dug and weighed, confidence bounds on the estimate of biomass were ± 29.1% of the estimate. By contrast, Table 2 shows that there is no such relationship between the CV of weight and the precision of biomass estimates. Thus, from the standpoint of statistical precision of the biomass estimate, the number of geoducks sampled for *weight* and the *variance of the mean weight* are irrelevant based on the tracts listed in Table 1.

The relationship shown in Table 2 between the CV of mean density and the 95% confidence interval makes it possible to predict with near certainty the precision of a tract's biomass estimate while still in the field, long before any geoducks are dug for weight samples.

A hand-held calculator with statistical function capabilities can be used to readily estimate the CV of density in the field, after transect surveys have begun. Actual geoduck counts from each completed transect may be used for this calculation, without applying either a show factor or converting the counts to a density estimate; CVs are unit-free relative measures of variance, and will therefore be identical in any case. The procedure is as follows:

1. Individually enter the geoduck counts from all transects (d_{obs}).

2. Have the calculator estimate the mean number of geoducks per transect and the sample variance (*Ex*: mean = 56.91 geoducks/transect and sample variance = 1,782.36).

Table 2. Sample size at 13 commercial tracts, coefficients of variation (CVs) for mean geoduck density and mean weight per geoduck, and the resulting 95% confidence intervals on the biomass estimates. Calculations are based on initial tract estimates.

Tract	Size (acres)	n (number of transects)	Transects / acre	Dig samples	Transects / dig sample	CV of mean density (%)	CV of mean weight (%)	95% CI on biomass (as % of *B*)
Arcadia 2	26	27	1.04	6	4.5	9.6	4.5	20.8
Bridge	35	34	0.97	4	8.5	14.5	6.9	31.5
Eld Inlet East	54	31	0.57	5	6.2	14.1	4.6	29.1
Arcadia 3	55	43	0.78	7	6.1	12.2	4.8	25.7
Eld Inlet West	79	47	0.59	14	3.4	14.1	2.7	28.1
Arcadia 4	118	82	0.69	14	5.9	7.8	4.3	17.5
Skiff Point	126	41	0.33	11	3.7	8.6	3.9	18.5
Blake Is North	144	61	0.42	6	10.2	12.7	6.5	28.0
Port Gamble	217	161	0.74	45	3.6	7.7	1.8	15.6
Murden Cove	222	68	0.31	19	3.6	7.2	3.1	15.4
Olele Point	225	91	0.40	16	5.7	6.8	2.9	14.5
Jamestown	255	67	0.26	9	7.4	8.6	3.3	18.0
Warrenville	316	102	0.32	8	12.8	13.4	5.2	28.2

3. Divide the sample variance by the number of transects to produce the variance of the estimator (*Ex*: n = 117 transects, so 1,782.36/117 = 15.23).

4. Take the square root of this number to produce the standard error of the estimator (*Ex*: square root of 15.23 = 3.90).

5. Divide the standard error of the estimator by the mean number of geoducks per transect and multiply by 100 to produce the coefficient of variation (*Ex:* CV = (3.90/56.91)100 = 6.85).

6. Double the CV to roughly estimate the width of the 95% confidence bound as a percentage of the biomass estimate (*Ex*: 2(6.85) = ± 13.7%. In this example, the precision lies well below the required limits of ± 30%, so that additional transects need not be taken). Doubling the CV roughly approximates the tabled t-value of 1.96 for an infinite number of samples (given a two-sided test with $\alpha = 0.05$), and is usually sufficient for *rough* field calculations.

If using this method to determine when enough transects have been run, it is important to note that this estimate of sample size may only be carried out *after* transects have been taken in a representative fashion throughout the entire tract (e.g., along grid lines spaced systematically every 1,000 feet apart). It is entirely possible, for example, to reach the desired statistical precision after only a few transects have been taken in a tiny corner of the tract; such a sample would be precise, but would very likely be biased. The same is true for geoduck weight samples which, to avoid bias, should be taken at systematic, random, or stratified random intervals throughout the entire tract.

Additional transects may be needed for certain tracts to reach the desired level of precision. Placement of additional transects within a tract is discussed below in the section *Variations on the standard grid line layout*.

Rationale for Systematic Sampling

A systematic grid sample was chosen to estimate geoduck biomass rather than a simple random sample for reasons of cost and convenience. To avoid decompression sickness, divers are limited in the amount of time they may spend sampling at depth, so that economizing bottom time becomes a paramount consideration in choosing underwater sampling designs. Systematic samples provide far greater information per unit time than simple random sampling, as illustrated in the example below.

Each transect typically takes experienced divers four minutes to complete, plus the time required to descend and ascend from the dive. Divers generally take about one minute to descend, become oriented, and record initial data. When surfacing following the dive, divers must ascend at a rate between 0.5 and 1.0 ft per second. Additionally, WDFW divers are required by safety regulations to perform a three-minute safety stop at -10 to -15 ft on every ascent to decrease the risk of decompression sickness (WDFW Diving Operations Manual, November 1991). Thus, a single transect at -60 ft would take between 9 and 10 minutes, and a random sample of 50 such transects would require as much as 500 minutes of diver time; only 200 minutes of this time is actually spent surveying geoducks, while the remaining time is used for descents, ascents, and safety stops.

A systematic grid sample, on the other hand, is considerably more economical in terms of diver time because there is only one descent and one ascent per grid line. Thus, the same 50 transects taken along systematically-spaced grid lines (assume, for this example, ten grid lines and five transects per line) would require only 260 minutes of diver time, and only 60 minutes of this time is used in descents, ascents, and safety stops. In practice, the time savings of systematic sampling versus random sampling are even greater, because the US Navy Dive Tables require that bottom times be rounded up to the nearest five minute increment, thus imposing an additional "penalty" for numerous single-transect dives. The time savings of systematic samples over random samples increases on tracts which are extremely wide (i.e., where each line consists of many transects) and decreases on tracts which are narrow due to steeply sloping bottom contours. Extremely narrow tracts, however, may be economically sampled using systematically-spaced oblique or zig-zag lines (see *Variations on the standard grid line layout* below).

Besides the considerable savings in dive time, there are additional advantages to a systematic sample when surveying geoducks. Choosing a single random starting point along the shoreline and then spacing lines of transects every 1,000 feet is much simpler, with fewer start positions, and less prone to selection error than attempting to choose random 900 ft^2 samples throughout a tract. Systematic line sampling also permits the most precise mapping of boundaries and spatial patterns in geoduck density.

Despite the cost benefits of a systematic sample for geoducks, classic sampling theory cautions that there are two potential disadvantages to systematic sampling: 1) It is impossible to guarantee that the estimate of mean density derived from a systematic sample is unbiased, and; 2) It is not possible to obtain an unbiased estimator of the variance of mean density from a systematic sample.

While there is no guarantee, from a theoretical standpoint, that systematic samples of geoduck density will be unbiased, we believe that the sampling protocol outlined above is no more likely to produce biased estimates than a simple random sample of the same size. This is because there are no known biological gradients affecting geoduck distribution which occur systematically along the shoreline. Put another way, we know of no variations in geoduck density which occur periodically at 1,000-foot intervals along the shoreline. (Gradients in geoduck density do exist along shorelines, and some of these gradients are even predictable -- such as generally decreasing numbers of geoducks from the mouth of a bay to the stagnant head of the bay. But note that this is not a *systematic* gradient, and could be sampled in a representative way by both systematic or simple random schemes).

On the other hand, lines placed systematically along depth contours (or running parallel to the shoreline) invite biased results, because depth is a known biological gradient with respect to geoduck density (Goodwin and Pease 1991). This is particularly true of samples consisting of transects along only one or two such lines. Under the recommended sampling protocol above, each line of transects running from the shallow boundary of a tract to its deep water boundary cuts completely *across* the depth gradient, minimizing depth-related bias.

The second potential problem associated with systematic samples is that they do not produce an unbiased estimate of variance (in our case, variance surrounding the estimate of mean geoduck density). The sample design protocol used here calculates variance using the simple random sample formula. Thompson (1992) notes that this leads to unbiased variance estimates only if the population units are randomly distributed; in most natural populations, this procedure tends to overestimate the variance of the mean. Thus, estimates of variance surrounding mean geoduck density when using this sample design are likely to be higher than the true variance. This in turn will tend to inflate the variance estimate surrounding total biomass, and widen the 95% confidence bounds on biomass.

We believe that these are, on balance, minor concerns, and concur with Hilborn and Walters (1992) who recommend systematic samples over simple random samples for surveys of abundance.

Tract Mapping and Grid Line Placement Methods

Individual geoduck tracts are mapped prior to performing surveys. Precise mapping is required for the following reasons:

1. To provide an accurate estimate of the tract's total surface area, which is used in Equation 6 above to estimate harvestable geoduck biomass on the tract.

2. To provide surveyers with information on depth contours which may influence the alignment of the systematic grid lines (see *Variations on the standard grid line layout* below).

3. To provide surveyers with an estimate of the sample size (i.e., the number of transects) needed to meet the required level of statistical precision.

4. To provide surveyers and managers with an estimate of the labor and time costs required to survey the tract.

5. To provide a precise post-survey spatial mapping of both transect locations and geoduck densities within the tract.

6. To develop reproducible and verifiable survey results.

Tract mapping has evolved considerably since geoduck surveys began in Washington in the late 1960s. During these early years, survey locations were first estimated by eye and later came to rely on navigational fixes from LORAN equipment. In recent years, the availability of sophisticated electronic field equipment such as Differential Global Positioning Systems (DGPS) and laser range finders, as well as computerized Geographic Information Systems (GIS), has made it possible to plot survey locations and estimate the surface area of tracts far more precisely than in the past. The sections below describe the methods currently used to map tracts and lay out the sampling grid lines prior to a survey.

Tract Mapping and Surface Area Estimates

Tracts to be surveyed by WDFW are initially mapped by DNR at a scale of one inch = 1,000 ft using a survey-grade DGPS unit. For most current surveys, DGPS positions are justified and plotted on either the NAD 27 (North American Datum 1927) or the WGS 84 (World Geodetic Survey 1984) geographic survey datum. These maps show the shoreline, the inshore, offshore and side boundaries of the tract, and fixed aids to navigation which may be useful in laying out the systematic grid lines for the survey. Side boundaries for the initial tract map depend on information from previous surveys and other management considerations, and are likely to change once survey data are analyzed.

In the case of tracts which have never been surveyed before, exploratory dives are often made to determine the extent of commercial geoduck densities. These exploratory dives may involve underwater sledding, single "bounce" dives spaced haphazardly throughout the area, swims along the shoreline paralleling a depth contour, or haphazardly-placed transect surveys. Such exploratory dives, while useful in defining the geographic boundaries of a tract, do not constitute valid geoduck surveys and cannot be used to estimate either density or biomass for the following reasons: 1) The samples are not systematically or randomly placed, increasing the risk of bias; 2)

Sample size is usually too small to provide the required degree of statistical precision; 3) Variants on the transect method such as sledding or bounce dives cannot be reliably adjusted for either the area surveyed or by existing show factor data; and 4) Depth contour swims are likely to provide biased estimates of geoduck density because they parallel depth, a known biological gradient of geoduck density (Goodwin and Pease 1991).

Once the initial boundaries of a tract have been determined and mapped, estimates of a tract's surface area are estimated with a scaled overlay sheet. Overlay sheets available from the Washington Department of Natural Resources (DNR) Inventory Section are scaled to one inch = 1,000 ft, requiring that the map be scaled appropriately prior to estimating acreage. The overlay sheet is placed haphazardly over the map, and the number of dots on the overlay sheet lying within the tract boundaries is counted, each dot representing one acre. This procedure is repeated several times and the average is taken as the best estimate of surface area.

Tract area estimates are also made by digitizing tract boundary data in MapInfo, a computerized geographic information system capable of calculating surface area. For most current surveys, DGPS fixes based on either the NAD 27 (North American Datum 1927) or the WGS 84 (World Geodetic Survey 1984) datum are used as input. It is absolutely essential that the same datum be used in creating maps and fixing positions in the field, or huge discrepancies in positions and area estimates will result. These computer-generated estimates of tract area are used to verify the estimate produced by the dot-overlay method.

The surface areas of tracts based on the initial mapping almost invariably change following the survey and prior to finalizing the biomass estimates on a tract. Side boundaries, for example, are likely to shrink if surveys or subsequent information indicate that low geoduck densities, polluted areas, difficult digging conditions, or narrow "pinched" depth contours merit a smaller tract. Inshore boundaries may be moved deeper, for example, if surveys find rooted eelgrass within two vertical feet of the -18 ft MLLW contour. In such cases, only survey data taken within the revised tract boundaries are used in the final estimation of biomass. The side boundaries of a tract may also be expanded -- as in cases where surveyers discover that commercial geoduck densities exist beyond the initial mapped tract -- but in such situations a new map of the expanded tract is required.

Standard Layout of Systematic Grid Lines

Once the tract has been mapped, the beginning points for systematic grid lines of transects are determined and marked with buoys. Each line of transects begins at the -18 ft MLLW contour; this depth is determined in the field with a fathometer and a tidal correction factor from computer generated daily tide graphs for the area. A point along the tract's -18 ft MLLW contour is randomly selected and a heavily weighted buoy is dropped there. Buoys are subsequently placed at 1,000-ft intervals along the entire length of the tract's -18 ft MLLW contour. Distance between buoys is measured with a laser range finder; a band of reflective tape is wrapped around the top of each buoy to facilitate long distance laser fixes. If a laser range finder is not available, or if rough weather precludes its use, buoys may be placed using DGPS fixes. After this initial buoy placement, a diver descends and re-positions the line exactly along the -18 ft MLLW contour, if required, using a digital depth gauge and a correction factor from daily tide graphs for the area. The diver then anchors the buoy line in the substrate with two or three steel reinforcing bars.

Spacing grid lines every 1,000 ft ensures, in theory at least, that no point within the tract will lie more than 500 ft from the nearest surveyed point. There are cases, however, where systematic placement of grid lines results in larger unsurveyed areas. Because grid lines are spaced beginning from a random starting point, the final grid line on one side of a tract may end up, for example, 900 ft from the tract boundary. To make sure that no point on the tract lies more than 500 ft from the nearest grid line, there are three possible solutions in this example: 1) Extend the tract boundary anywhere between 100 and 600 ft, and run another grid line of transects 1,000 ft from the previous line; or 2) Move the tract boundary at least 400 ft closer to the grid line; or 3) Place another grid line of transects anywhere within 500 ft of the existing tract boundary. Since it is often impossible to extend tract boundaries (due to the presence of hazards, closed areas, other tracts, etc.), and because shrinking tract boundaries reduces fishing area, the third solution is used most frequently. For more details, see *Variations on the standard grid line layout* below.

Once buoys have been systematically placed along the -18 ft MLLW contour at 1,000 ft intervals, the buoy positions are mapped. Whenever possible, buoy positions are mapped with a combination of DGPS fixes and laser range-finder fixes. Laser fixes rely on triangulation of laser ranges between the buoy and clearly identifiable landmarks appearing on the DNR-generated maps (e.g., fixed navigational aids, bridges, towers, jetties, docks). The laser range-finder currently used is capable of fixing positions marked with a reflective mirror from as far away as 4.8 km. Figure 4 shows and example of buoy mapping on a geoduck tract. On some tracts, it is impractical to shoot laser ranges to shore; in these cases DGPS fixes may be sufficient.

Once these steps have been taken to map the tract, dive surveys are initiated beginning at each of the anchored buoy lines. A series of 900 ft^2 transects are taken along a compass bearing headed directly offshore from each bouy. Figure 3 shows a typical survey layout with grid lines spaced at 1,000-ft intervals and running directly offshore.

Variations on the Standard Grid Line Layout

On some tracts, the survey layout described above -- systematic grid lines running directly offshore every 1,000 feet along the -18 ft MLLW contour -- requires modification. Variations on the standard layout are sometimes required for one or more of the following reasons:

1. To increase cost-effectiveness of the survey in terms of transects surveyed per unit of diver bottom time.

2. To reduce the likelihood of bias due to nonrepresentative sampling of the tract area.

3. To meet the required standard for statistical precision described above.

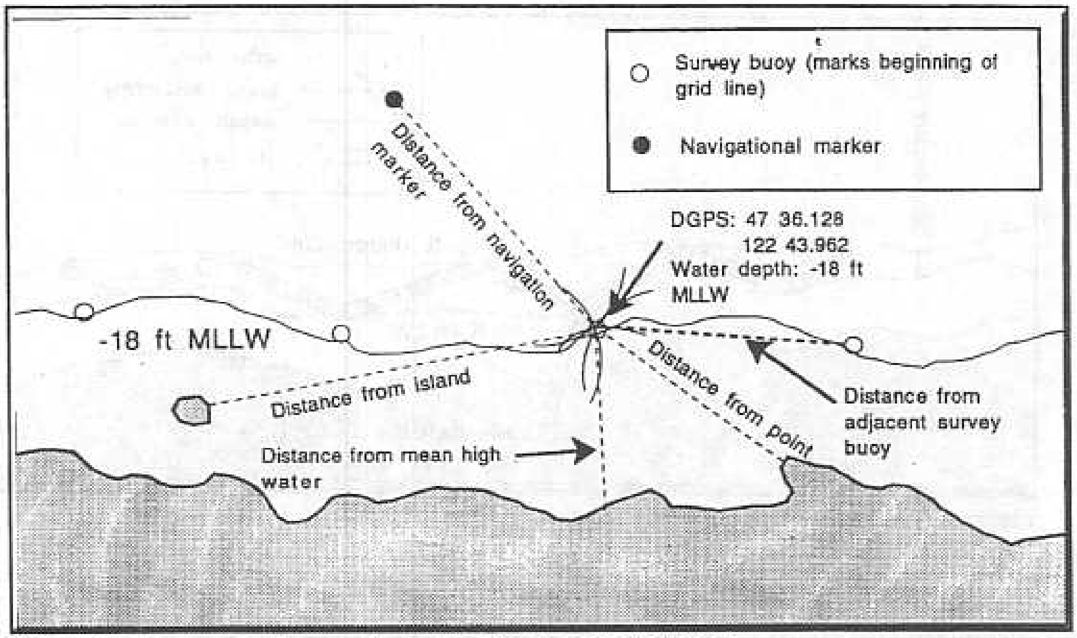


Figure 4. An example of survey buoy mapping on a geoduck tract.

Steep, narrow tracts frequently require a slightly different grid line layout to meet all three of the above goals. On such tracts, the steeply-sloping bottom often allows room for only one 150-ft long transect before divers reach the -70 ft contour. This single transect will require roughly ten minutes of bottom time, only four minutes of which are spent counting geoducks; the other six minutes are used on the descent, ascent, and three-minute safety stop.

In addition to being wasteful, a series of such single transects on a very narrow tract invites bias. This occurs when divers reach -70 ft prior to finishing the transect, and turn to finish the transect along the -70 ft contour. On long, narrow tracts, this may occur so often that a large proportion of the sampling effort takes place along the -70 ft contour. As noted earlier, depth is a known biological gradient with respect to geoduck density (Goodwin and Pease 1991), and transects running parallel to any depth contour are therefore a source of potential bias in the density estimate.

Finally, narrow tracts often fail to produce biomass estimates of the required statistical precision. This is because only one or two transects are possible every 1,000 ft, resulting in a low sample size (unless the tract is extremely long).

To remedy these problems on narrow tracts, grid lines are sometimes placed along oblique or zigzag angles rather than perpendicular to shore. Figure 5 shows examples of oblique and zigzag lines on narrow tracts. Obliques and zigzags allow more back-to-back transects to be surveyed before divers must surface, thus providing more information per unit time, as well as a larger sample size per length of tract shoreline. In the case of zigzag lines, the likelihood of bias is also reduced, because divers immediately turn inshore upon reaching the -70 ft contour, continuing to cut across depth gradients rather than surveying parallel to them.

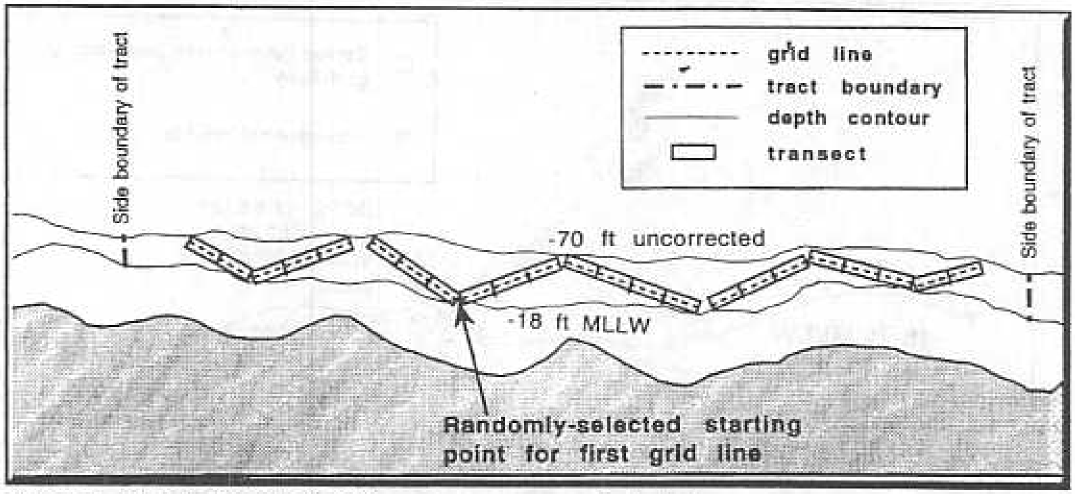


Figure 5. Zig zag layout of grid lines on a narrow geoduck tract.

On some tracts -- usually small tracts, or those with highly variable geoduck density -- grid lines spaced systematically every 1,000 ft do not result in biomass estimates of the required statistical precision. Increasing the sample size (i.e., running more transects) is sometimes the answer. This is accomplished by splitting the existing grid lines -- in other words, running lines of transects every 500 ft rather than every 1,000 ft. Note, however, that to reduce the chance for sampling bias, new grid lines must be run between *all* existing lines rather than a select few. There is no limit on the number of times existing lines may be split in this manner to obtain more transects, but there are diminishing returns with respect to precision as sample size increases.

Strict adherence to systematic spacing of grid lines may sometimes result in samples that are not spatially representative of the tract, and are thus likely to be biased. As noted above, the goal of unbiased surveys is to ensure that no point on the tract lies more than 500 feet from the nearest grid line of transects. Because the grid lines are spaced beginning from a random starting point within the tract (rather than the tract boundary itself), situations may arise in which the final grid line of transects lies more than 500 ft from the tract boundary. As noted above, this is most easily remedied by simply adding another grid line of transects anywhere within 500 ft of the tract boundary. The shape of the shoreline may also require additional grid lines. Figure 6 shows an example in which, due to the shape of the shoreline, a large area of the tract would remain unsurveyed with systematically-spaced grid lines. In this example, the logical (but entirely *ad hoc)* remedy was adding another grid line of transects in the middle of the unsurveyed area, such that no point on the tract lies more than 500 ft from the nearest grid line. Similar *ad hoc* sampling schemes are sometimes called for on tracts with "dog-leg" shorelines, islands, or other unusual geographic contours.

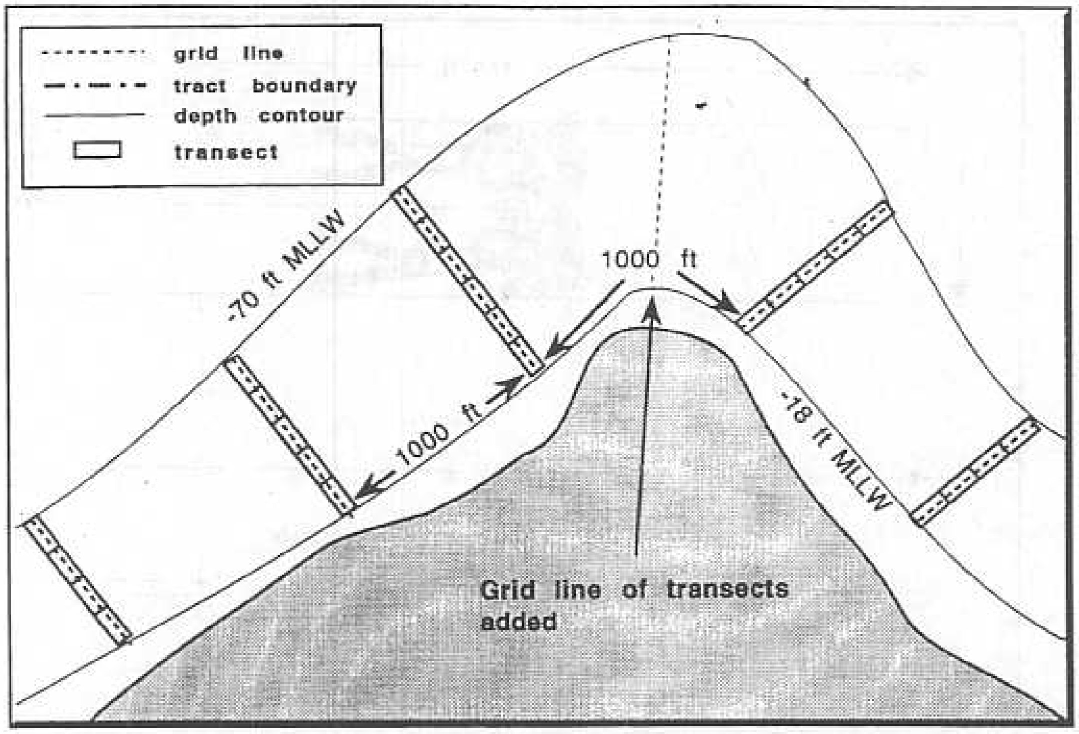


Figure 6. *Ad hoc* placement of an additional grid line of transects to achieve representative sampling of a large area of the tract.

Geoduck Survey Methods

Strip Transect Surveys

To estimate the number of harvestable geoducks within each 900 ft^2 transect, two divers swim side by side, each counting all geoduck siphons, or marks in the substrate which are judged to have been made by geoducks (also called "shows" or "dimples;" see the section *Identification of geoduck shows* below). An individual diver is responsible for counting the geoduck "shows" directly underneath his or her half of the six-ft wide transect rod and spool (Figure 7). Thus, each diver surveys a swath three-ft wide by 150-ft long. The sum of the two diver counts on an individual transect is the total observed number of harvestable geoducks on that transect (d_{obs} in Equation 1 above). In order to ensure consistent transect length and area, the transect line is periodically re-measured to detect and correct any stretch or shrinkage.

An individual diver attempting to survey geoducks in swaths wider than three ft will generally produce unreliable counts, due to the subtle character of geoduck shows and the poor underwater visibility in Puget Sound. Double counting of geoducks may occur when a diver must scan more than three feet in high-density geoduck areas. An additional problem with variants on the historically-used three-ft transect width is that geoduck show factors used in adjusting density have only been estimated on show plots of this width (see *Show plot surveys and show factors* below). Use of a different transect width may invalidate the use of the currently-accepted 0.75 show factor and require additional studies.

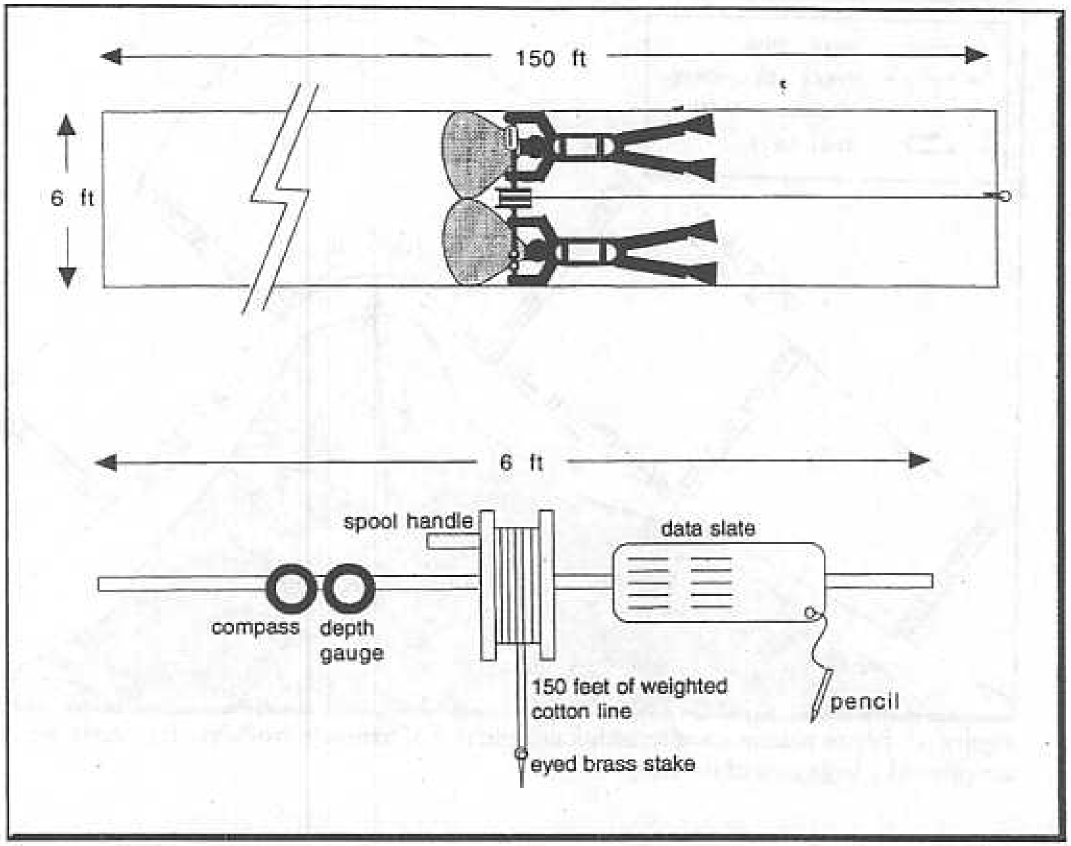


Figure 7. Two divers performing a strip transect survey of geoducks within a 900 square foot transect, and details of the transect pool.

The transect is initiated by planting a metal stake in the substrate which temporarily anchors the 150-ft long transect line. The first transect along any systematically-placed grid line begins at or near the anchored buoy marking that line along the -18 ft MLLW contour (see the section above). A compass course is determined prior to entering the water, generally directing the long axis of the transect perpendicular to the shoreline; oblique or zig-zag courses are sometimes used in surveying extremely narrow tracts as described above. Divers swim along the compass course and away from the shoreline, unspooling the 150-ft transect line as they swim. Each transect typically requires about four to five minutes.

If at the end of the 150-ft line, the -70 ft (uncorrected to MLLW) water depth has not been reached, another transect is initiated along the same compass course. The divers signal the start of each new transect for the boat tender by separating approximately 15-20 ft. One diver remains at the ending point of the transect, recording data for the transect on a dive slate, while the second diver swims back along the transect to respool the transect line. Meanwhile, the tender boat hovers near the divers' bubbles to record the starting position of each transect based on this separation of bubble streams (see *Recording data* below). When the -70 ft water depth is reached, the divers return to the surface and are moved to the next transect buoy to begin another line of transects. If divers reach -70 ft prior to reaching the end of the 150-ft long transect, they turn (generally upcurrent) and finish the transect obliquely toward shore. If a transect ends slightly shallower than the -70 ft contour, divers generally return to the surface; this avoids the potential bias inherent in counting a transect which lies almost entirely along a depth contour.

Lines of such transects are completed at systematic intervals throughout the bed, generally spaced 1,000 ft apart, until the entire bed has been surveyed at a sampling intensity which produces biomass estimates of a specified statistical precision (see the sections *Precision of geoduck biomass estimates* and *Sample size* above).

Identification of Geoduck Shows

Geoduck siphons, when exposed above the surface of the substrate and pumping water, are easily recognized by their large size, elliptical or oblong shape, a flat (rather than rounded) siphon tip, the absence of tentacles along the inner portion of either siphon opening, and the fact that both siphon openings are the same size. When partially retracted, geoduck siphons may be identified by their elliptical or oblong shape, flat siphon tip, and sometimes by the presence of pellet-like particles of undigested particulate matter (pseudofeces) lying on the surface near the siphon tip. Such "dimples" may be probed with thin neoprene finger gloves for verification; geoducks have a characteristically soft, rubbery texture (as opposed to a slimy feel) with no horny plates on the siphon tip. When probed in this manner, geoducks typically retract their siphons slowly.

Subtidal geoduck tracts almost always contain other animals, however, whose siphons or shows may be confused with geoducks by inexperienced divers. These include other molluscs such as horse clams (*Tresus capax* and *T. nuttallii*), false geoducks (*Panomya* spp.), piddock clams (*Zirfaea pilsbryii*), cockles (*Clinocardium nuttallii*), horse mussels (*Modiolus rectus*), and truncated softshell clams (*Mya truncata*), as well as animals from other phyla (retracted sea pens, for example). Density and biomass estimates will obviously be biased if surveyers count these animals as geoducks, or if they fail to count geoducks under the assumption that they are something else.

Figure 8 shows the major differences between geoducks and those of other subtidal molluscs. Harbo (1997) provides an excellent chapter on siphon identification, including a key and color photographs of many north Pacific clam siphons. WDFW staff provide an annual class on geoduck survey methods which includes color slides of clam siphons and a touch tank containing various clam species buried up to their siphons. The class is open on a first-come basis to tribal shellfish biologists and biologists employed by ecological consulting firms.

The animals most easily confused with geoducks during subtidal surveys are horse or "gaper" clams of the genus *Tresus*. Two characteristics of the siphon tip serve to distinguish both species of horse clams from geoducks: 1) The presence of an inner ring of tentacles on the horse clam's siphon, and; 2) The presence of horny plates surrounding the siphon tip of horse clams. The tentacles are obvious when horse clam siphons are open and pumping. When the siphon is closed, or when the tip is not visible, divers with thin neoprene finger gloves can often probe the siphon and feel the horse clam's horny plates. Typically, horse clam siphons are oval or nearly round in cross-section, while geoduck siphons are elliptical. Horse clams generally retract their siphons faster than geoducks when disturbed, expelling a jet of water. Finally, horse clam pseudofeces are thin and stringy rather than pellet-like.

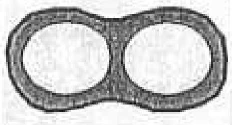
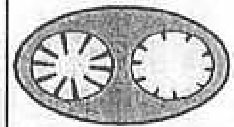
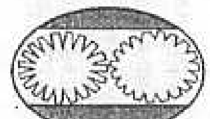
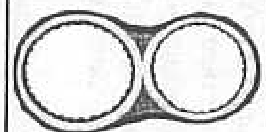
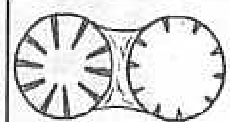
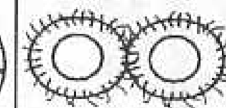
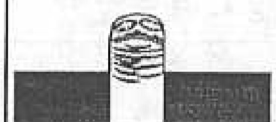
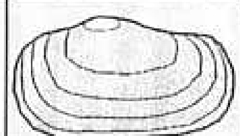
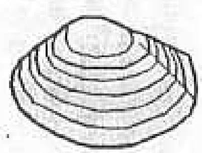
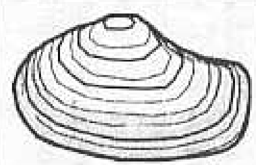
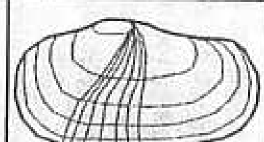
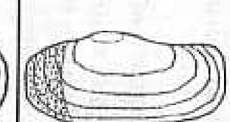
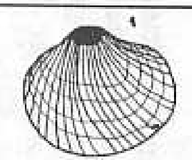
Scientific Name	*Panopea abrupta*	*Tresus sp.*	*Mya truncata*	*Panomya sp.*	*Zirfaea pilsbryii*	*Clinocardium nuttallii*
Common Name	GEODUCK	HORSE CLAM	TRUNCATED MYA	FALSE GEODUCK	PIDDOCK	COCKLE
siphon shape (topview)	 "Double Barrel Shotgun"	 Oval	 Oval	 "Double Barrel Shotgun"	 Bifurcated	 Two Circles
siphon shape (side view)						
tentacles	absent	present/distinct	present/fine	present/very fine	present/distinct	present/distinct
substrate depth	18 to 36 inches	8 to 15 inches	8 to 10 inches	8 to 15 inches	8 to 20 inches	at surface
substrate type	all (except clay)	grvl/cbble/sand	mostly mud/snd	all (except clay)	clay/rock/wood	snd/snd-mud
shell						
siphon color	brown to light brown w/ cream interior	grey/blue tentacles w/ brown exterior	dark brown w/ heavily wrinkled siphon	brown to light brown w/ red and cream circling siphon	mottled reddish and brown with cream white	creamy brown
other distinguishing features	large siphon, smooth/soft, obvious pseudofeces	horny plates on siphon, encrusted plates, hard tip when probed	leathery flaps, index finger shape to siphon	large, thin walled siphon, smooth/soft, different size siphon openings, cleft in shell, obvious pseudofeces	bifurcated siphon, slimy thin feel, toothed shell	"furry" look to siphon, very shallow, heavy round shell

Figure 8. Quick reference for subtidal clam identification.

False geoducks (*Panomya* spp.) are generally smaller than geoducks, and have a distinctive siphon tip with a thin pink or red ring encircling each siphon hole. Even when this color is not apparent, *Panomya* siphon tips appear rounded in side profile, as opposed to geoduck siphon tips, which are box-like when viewed from the side. *Panomya* can also be distinguished by their thinner siphon membranes and because the incurrent siphon, when open and pumping, is noticeably larger than the excurrent siphon. *Panomya* have a barely visible inner ring of very fine tentacles on the siphon.

Mya truncata are usually much smaller than geoducks, and have a thin, dark-brown, wrinkled siphon with leathery flaps at the tip. Piddocks (*Zirfaea pilsbryii*) are easily distinguished from geoducks by their bifurcated (forked) siphons, maroon or dark red siphon tips, and a distinctive white and reddish brown mottled pattern on the siphons. Piddock siphons are also very thin-walled and have a slimy, smooth feel unlike the rubbery siphon covering of geoducks. Piddocks are boring clams, and are therefore found only in substrates such as clay and wood, although this may not be readily apparent if there is a thin surface layer of sand or mud. Cockles (*Clinocardium nuttallii*) are readily distinguished by their white, "furry" siphon tips; they can also be easily dug by hand to verify their identity, since they do not burrow deeply into the substrate. The siphon of the horse mussel (*Modiolus rectus*) appears as one or two narrow slits, usually in muddy substrates. Because the shell lies immediately below the substrate, they are easy to verify by hand-digging.

Non-molluscans such as sea pens (*Ptilosarcus gurneyii*) can sometimes produce a geoduck-like "dimple" when they are retracted into the sand. When probed, they feel soft to the touch like a geoduck siphon. But because sea pens have no siphons, they cannot retract further into the substrate when probed by hand. When visible, sea pens are a distinctive bright orange color.

The field experience of surveyers is crucial when distinguishing geoduck shows and siphons. New WDFW surveyers gain such experience in part by making practice "surveys" with experienced biologists, and by positively verifying their siphon identifications with dig samples. When making transect counts, WDFW surveyers include only shows which can be readily identified as belonging to a geoduck.

Recording Data

At the start and finish of each transect, the divers record water depth (i.e., ambient depth uncorrected to MLLW) to the nearest ft using a digital depth gauge. At the end of the transect an assessment of the surface substrate composition is recorded. The substrate is assigned one or a combination of the following categories: mud (<63 microns), sand (63 microns-2 mm), pea gravel (2-20 mm), and gravel (>20 mm). Particle sizes and the dominant substrate throughout the length of the 150-ft transect are judged subjectively by the surveyers, and are not quantitatively measured with traditional screening techniques. Cobble, boulders, logs, wood debris, and other features associated with the substrate (e.g., sandy hummocks) are also recorded when present. The presence of readily visible macro flora and fauna is also recorded, including eelgrass, major algal groups, major epibenthic animals, and fish. The boat operator, hovering above the divers' bubbles at the start of each transect, records DGPS latitude and longitude to the nearest thousandth of a minute. Starting time for each transect is also recorded, so that the uncorrected transect depth reported by the divers may be later corrected to MLLW with the use of a tide graph for the area. DGPS latitude and longitude are also recorded at the end of the final transect in any line of continuous transects.

Appendix 1 contains sample data sheets. Appendix 2 lists the codes used for recording substrate composition and associated plant and animal data.

Geoduck Dig (Weight) Samples

As noted earlier, cluster samples of geoducks (called dig samples) are taken systematically at every sixth transect previously surveyed for density. Transects where the density of geoducks falls below currently accepted commercial levels (i.e., <0.04 geoducks per ft^2) are eliminated from this selection process. The dig samples provide an estimate of mean weight per geoduck (Equation 4), as well as information on market quality, difficulty of digging, and substrate composition below the surface layer.

Using DGPS fixes and corrected depth data from the transect surveys, the boat is anchored near the middle of each systematically-selected digging transect. A single line-tended diver descends immediately below the boat and haphazardly digs the first ten visible geoducks. The diver also records information on the surface substrate composition, the water depth at which geoducks were dug, and a subjective evaluation of the ease or difficulty of digging. The boat crew records DGPS latitude and longitude of the digging location, the number and condition of geoducks dug, and the time taken to dig the samples. The geoducks taken at each transect are kept separately in moist burlap sacks labeled with the transect number, and are periodically soaked with seawater to keep them alive. Appendix 1 contains an example of the data recorded for a typical dig transect.

The geoduck samples are kept cool and moist in burlap sacks, transported to the Point Whitney Shellfish Laboratory, and either processed the same day or placed in running sea water for later processing. Processing occurs as soon as possible to avoid mortalities which may result from injuries sustained during digging. Whole wet weight (grams) is measured after a drainage time of a few minutes to two hours. All geoducks are weighed, but damaged clams -- those with broken valves or tissues blown apart by the water jet -- are noted and eliminated from the calculation of mean weight. The greatest anterior-posterior length of the right valve is measured with calipers to the nearest mm. The right valve is the valve on the observer's right side when the clam is held with the siphon down and the umbo facing the observer (Figure 9). The siphon is then cut from the body (Figure 9) and weighed separately. Siphon weight information is valuable for commercial marketers, since the siphon is the portion of the geoduck which currently determines the market price in many cases. Overall geoduck quality, which is a function of gross appearance, color, and size, is then judged as either commercial or non-commercial. Appendix 1 shows an example of typical weight and quality data as recorded on the data sheet.

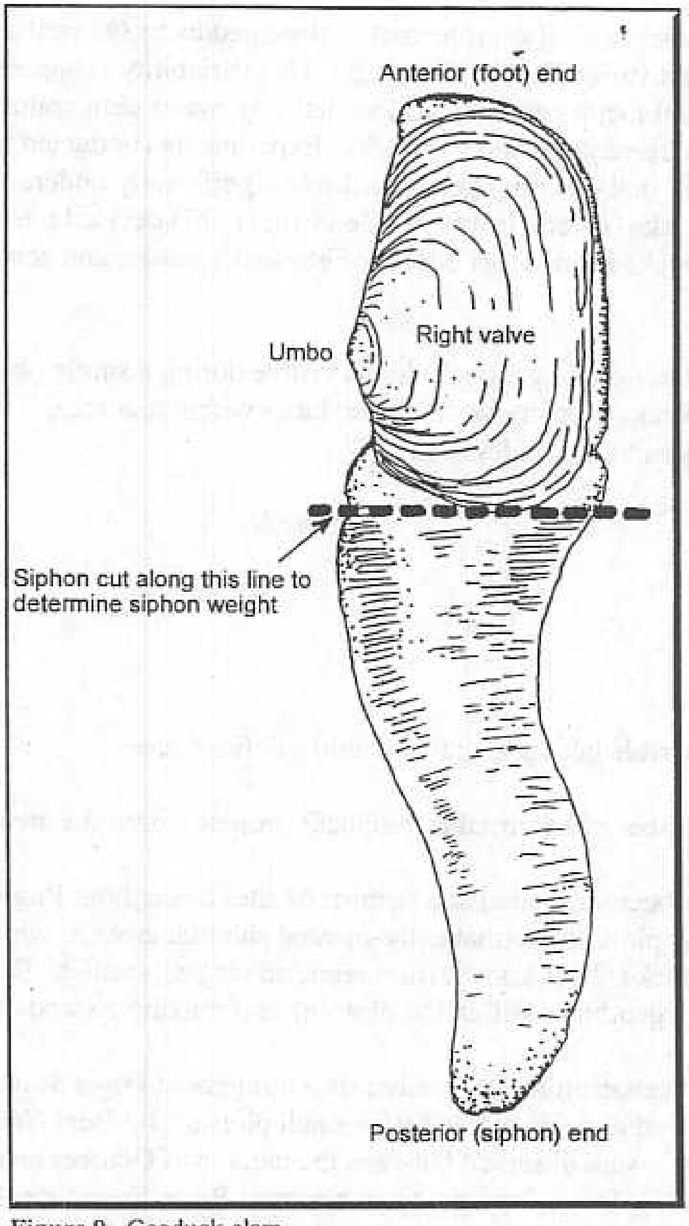


Figure 9. Geoduck clam.

Show Plot Surveys and Show Factors

A geoduck "show" is either a geoduck siphon visible above the substrate surface or a depression left in the substrate which can be identified as having been made by a geoduck siphon (Goodwin 1973). The only practical way to estimate geoduck density is to count such "shows" within measured transects. Digging numerous samples from the substrate, a method commonly employed to estimate the density of small intertidal clam populations, is not feasible for geoducks on a large spatial scale because they are buried too deeply in the substrate.

Counting shows, however, is also problematic, since geoducks (as well as other clam species, see Flowers 1973) exhibit variability in "showing." This variability is apparently a function of various environmental factors such as food availability, water temperature, substrate type, algae cover, turbidity, and currents (Goodwin 1977). Experiments conducted in Washington in the early 1970s indicated that counting geoduck shows significantly underestimated the true density of harvestable geoducks (Goodwin 1973). Goodwin (1977) devised methods of estimating the true density of geoducks from visual counts of geoducks shows, and coined the term "show factor."

The show factor is the ratio of geoduck shows visible during a single observation of any defined area and the true abundance of harvestable geoducks within that area. The show factor (S) is expressed as a proportion, and calculated as

$$S = n / N \quad . (9)$$

where

S = show factor

n = the number of visible geoduck shows within a defined area

N = the absolute number of harvestable geoducks present within the area

This proportion has been estimated at a number of sites throughout Puget Sound with the use of "show plots." Show plots are permanently-marked subtidal areas in which the absolute number of harvestable geoducks (N) is known from repeated tagging studies. Divers then revisit the plot and count all visible geoducks within the plot (n) as if making a standard survey.

Show factors have been estimated at twelve sites throughout Puget Sound from 1984 to 1993. Goodwin (1977) found a seasonal trend with small plots at Big Beef Creek, Hood Canal, where zero or few geoducks were observed between the months of October and March. The average monthly geoduck show factor from the twelve sites in Puget Sound reached an average maximum for March of 0.73 (i.e., only 73% of the geoducks present would be expected to be observed during an instantaneous count by divers). There were small incremental declines each month to 0.54 in September and to 0.43 in October. Show factors also vary from year to year. For example, the average annual geoduck show factor for all show plots in 1986 was 0.51. In 1992, the average annual geoduck show factor for all show plots was 0.77. The Puget Sound average show factor for all show plots from 1984 to 1993 is 0.62.

Since establishing show plots for a tract is extremely time consuming, state and Tribal managers have agreed to use a show factor of 0.75 to estimate biomass for pre-fishing surveys on a given tract. In other words, we assume that 75% of the harvestable geoducks present are actually seen and counted during an instantaneous transect count. Using a standard show factor avoids the time and expense of establishing separate show plots for each tract being surveyed. A show factor of 0.75 is, for most tracts, conservative and will not lead to overestimation of geoduck biomass on a given tract. A show factor of 0.75 is used to estimate density on all tracts for pre-fishing surveys, unless there is a show plot established for a tract that will give site-specific data.

Some situations may arise in which surveyers may wish to establish a show plot despite the cost and time involved. Examples include: 1) Surveys carried out in habitats or depths for which no historical show plot data exist; 2) Surveys where risk-averse management policies dictate that a conservative (i.e., low) show factor be used (as, for instance, when geoduck densities below a certain threshold would permit developers to destroy a potentially commercial geoduck tract); 3) Surveys using non-standard methods (e.g., quadrat counts, transects more or less than three feet in width); and 4) Surveys carried out by inexperienced divers who wish to verify their counts. The following paragraphs describe the field methods used to establish and count a show plot.

Show plot surveys are carried out during the period March 1 - October 14, when geoducks are actively pumping water and the the show factor is highest. Show plot counts made during the fall and winter are likely to underestimate the actual number of geoducks present within the plot because of the documented low show factor (Goodwin 1977), or else would require unreasonable effort and time to be certain that all geoducks within the plot had been detected.

Show plot sites are selected so that they are close to the tracts or areas being surveyed and to mimic, as closely as possible, the substrate and current conditions of the survey tract or area. Obviously, show plot sites must contain geoducks in roughly commercial densities. Show plots are usually situated along a depth contour which is midway between the depths being surveyed at the nearby tract or area. For example, most show plots for commercial geoduck surveys, which take place between the -18 ft MLLW and -70 ft contours, are situated at the - 40 ft MLLW depth. To avoid destruction of the show plot boundary markers, show plots are not sited in areas where boats frequently anchor or where tidal currents sweep large amounts of algae along the bottom. Finally, show plots are not sited in areas with large populations of horse clams (*Tresus* spp.), which might confound the results.

Once a suitable site has been chosen, yellow polypropylene lines are staked on the bottom to delineate a standard 900 ft^2 geoduck transect, including a line down the center of the six-ft wide transect. In this way, two three-ft wide strips running for 150 ft are outlined with yellow line. Corners of the plot are staked with steel reinforcing bar, and the line is staked at intervals with smaller metal stakes to prevent the line from floating above the substrate.

Following placement of the plot boundary markers, divers begin "tagging" all geoducks which are showing within the plot. Two divers slowly swim the entire plot, each diver being responsible for his or her three-ft wide half of the plot. Geoduck shows are tagged by placing a sturdy wire stake -- usually 3/16 inch diameter and 12 inches in length -- next to the siphon. All such tags are oriented to either the left or right of the siphon to avoid confusion with other shows, and are carefully placed about 1.5 inches from the siphon to reduce the risk of injury to the animal. Tags are set roughly six inches into the substrate wherever possible. During tagging, divers situate themselves perpendicular to their half of the plot to prevent fins from dislodging tags that are already in place.

All geoduck shows are tagged in this manner throughout the show plot over a period of several days. Following each tagging session, divers record the total number of tags placed. Each successive tagging session requires fewer new tags, in the manner of classic "removal sampling" methods (Zippin 1956; Seber 1982). In this case, geoducks are "removed" by tagging, and we assume that the entire population within the plot has been censussed when, after several repeated tagging sessions, no new tags are required. This point is generally reached after about five days in most geoduck show plots, although tagging must continue as long as new shows are discovered during the previous tagging session. Several tagging sessions are sometimes done during a single day to speed up the "removal" process (i.e., to reach the point where repeated sessions encounter no new shows). However, repeated tagging sessions during the same day run the risk that at least some geoducks will not show because they have been disturbed by the divers, and therefore tagging should span a minimum of three days. To avoid bias of this sort, the final determination of complete "removal" is made on a day when no previous tagging sessions have occurred.

After repeated tagging sessions result in no new shows, divers carefully gather all tags from the plot and the total number of tags from both halves of the plot is assumed to represent N, the absolute number of harvestable geoducks within the plot.

Once N has been established, it is possible to estimate show factors by returning to the plot and counting the number of shows as if surveying a standard 900 ft^2 transect. Without disturbing geoducks, two divers locate the show plot and begin a routine transect survey, using the polypropylene line boundaries rather than the transect spool to delineate the transect. Each diver swims his or her half of the plot at a speed which is consistent with the swimming speed during normal transect surveys (roughly 4-5 minutes for a 150 X 6 ft transect), counting all shows. The total number of shows (n) is divided by N (known from the repeated tagging done previously) to produce the estimated instantaneous show factor (S) as in Equation 9. Site specific show factors may be estimated in this way for successive days, weeks, or months; estimates after a year run the risk of bias due to changes in the geoduck population within the plot (N) due to recruitment or mortality. In estimating show factors on a daily basis, divers are rotated to reduce the chance of bias from an individual diver remembering the location of certain geoducks within the plot (Goodwin 1977).

Seasonal Considerations for Geoduck Surveys

State and Tribal managers have agreed that geoduck surveys will not made from October 15 through February 28, due to the low "show factor" of geoducks during the winter months (Goodwin 1977). Surveys made during this period of time would tend to produce highly unreliable density estimates; see the section *Show plot surveys and show factors* above.

Eelgrass Surveys

Eelgrass (*Zostera marina*) provides important habitat for juvenile Dungeness crab, spawning herring, and other marine animals. The WDFW Habitat Division requires that geoduck harvest not occur within eelgrass beds. Prior to fishing, eelgrass associated with geoduck beds is surveyed and a two foot vertical buffer is established around occurrences of rooted eelgrass. On a tract where the slope is very slight, using this standard two-ft vertical buffer may needlessly exclude large portions of the commercial tract. Under these circumstances, a 180-ft horizontal buffer (seaward and deeper than the deepest eelgrass) may be used. Geoduck harvest is not allowed within these buffer zones. Thus, eelgrass surveys are an integral part of every pre-fishing geoduck survey, because eelgrass distribution determines the inshore or shallow boundary of the geoduck tract in many cases. This inshore boundary is required for a determination of total surface area, used in Equation 6 to estimate total geoduck biomass on the tract.

To determine whether the standard two foot buffer zone below eelgrass impinges on a commercial tract's inshore boundary (normally set at -18 ft MLLW), pre-fishing eelgrass surveys are conducted by divers swimming along the -16 ft MLLW contour. Occurrences and extent of eelgrass found deeper than -16 ft MLLW are noted using DGPS latitudes and longitudes. When eelgrass occurs deeper than -16 ft MLLW, divers characterize the occurrences, define the perimeter of eelgrass beds, and note the water depth at the deepest occurrence of eelgrass for that site. Normally a two foot vertical buffer along the entire length of the tract is set below the deepest occurrence of any rooted eelgrass found along the tract. Alternatively, a buffer zone of at least 180 ft around eelgrass beds deeper than -18 ft MLLW can be used when the tract is marked to exclude eelgrass and the marking is visible to divers within the tract.

Labor Costs of Geoduck Surveys

Table 3 shows the field time spent surveying geoducks at four recently-surveyed tracts, and provides a rough planning guide. Survey time includes not only running transects and digging geoduck samples, but also includes boat transit to and from the tract, boat maintenance, eelgrass surveys, and the placement and mapping of buoys which mark the sample grid lines. Laboratory time (weighing geoduck samples) and the time required for data entry and analysis, however, are not included here.

Table 3. Time budget (in person-hours) for geoduck field surveys at four commercial tracts.

Tract	Size (acres)	Transects / Acre	Transect Survey Time (hrs)	Dig Sample Time (hrs)	Tract Mapping Time (hrs)	Eelgrass Survey Time (hrs)	Boat Maintenance Time (hrs)	Transit Time (hrs)	Total Time (hrs)	Hours / Acre
Agate Pass	945	0.34	404	128	52	64	48	12	708	0.75
Jamestown	300*	0.36	164	24	4	64	20	12	288	0.96
Olele Pt	160	0.59	174	56	28	48	4	12	322	2.01
Pt Robinson East	22	1.18	44	12	4	0**	0	12	72	3.27

* The data for this tract represent an initial survey area.
** Eelgrass surveys were not performed at this tract because the inshore tract boundary for non-Indian divers was roughly -35 ft MLLW throughout the tract, well below the deepest occurence of eelgrass in Puget Sound.

As shown in Table 3, transect surveys consume most of the total geoduck survey time. Transect surveys required between 54 - 61% of the total survey time at the four tracts. Note that the "transect survey time" in Table 3 includes not only actual diver bottom time, but also include all hours worked by the non-diving team aboard the boat, time spent during surface intervals, time spent suiting up, recording data, and other miscellaneous "diving" tasks which do not actually occur underwater.

Table 3 also suggests that as tract size decreases, the survey time required per unit of surface area increases. This occurs primarily because small tracts require more transects per acre to reach the statistical precision requirements (see *Sample size* above).

Surveys are usually conducted by four divers. A team of two divers begins the day by running transects until their no-decompression bottom time is expended. Meanwhile, the two remaining divers operate the boat, keep track of the divers, and record position and time data for the transects. The second team continues transect surveys while the first team completes a surface interval. Following the surface interval and the ascent of the second team, the first team typically re-enters the water to continue transects until their bottom time is expended. Digging typically requires one diver who actually digs the geoduck samples and at least two crewpersons who operate the boat, water pump, safety line, and record data.

Bottom times for WDFW divers must comply with the US Navy Tables, and each ascent must include a mandatory three to five-minute safety stop at -15 ft. Therefore, divers who utilize computers or who do not make recommended safety stops would obviously require less time to complete transect surveys and dig geoduck samples than WDFW divers.

Environmental Assessment

Geoduck beds which prove to have commercial concentrations of geoducks are then further studied. Inquiries are made to various agencies and groups to obtain additional ecological information, and to learn of possible interaction between geoduck fishing and other uses of the areas.

Washington Department of Ecology is contacted for water quality information. Divisions within WDFW and local Tribes are contacted to learn of sensitive habitats, important resources, or activities that may be affected by geoduck fishing. The county in which the proposed fishing will occur is contacted to learn of the shoreline designation of areas adjacent to geoduck beds. After receiving comments from all of the groups contacted, an environmental assessment is written by WDFW for each proposed geoduck fishing location.

The environmental assessment describes the size and location of the proposed tracts. Tract substrates and water quality are summarized, as well as the geoduck abundance, size, and quality. Other biota including fish, invertebrates, aquatic plants, marine mammals, and birds are discussed. The last part of the assessment covers activities including fishing, navigation (boat traffic), and other uses.

DNR then writes an adoption notice and notifies shoreline owners and other members of the public of the planned fishery.

Part II Equilibrium Yield Modeling

Methods

Data

Over 2,000 geoducks were sampled between 1979 and 1981 at 15 previously unharvested sites in Puget Sound and the Strait of Juan de Fuca to obtain information on age distribution and growth (Figure 10). The sites span four of the current six geoduck management regions, with six sites in the Hood Canal region, two sites in the Central Sound region, one site in the Strait region, and two sites in the South Sound region. Samples were taken randomly within each site at depths of -30 to -60 ft MLLW by washing geoducks from the substrate with a commercial water jet. Age was determined from annual growth increments in the hinge plate using the acetate-peel method (Shaul and Goodwin 1982). The von Bertalanffy growth parameters (L_∞ , k , t_0) were estimated for each of 234 sub-sampled geoducks with a nonlinear regression method. A two-factor ANOVA was used to test if growth parameters differed within or between management regions. Hoffmann *et al.* (1999) provide a detailed description of the growth analysis.

Equilibrium Yield Model

Geoduck yield was modeled using a deterministic, age-structured equilibrium yield model. Given a set of parameter estimates for mortality, maturity, growth, and selectivity, the model collapses the number of geoducks at age for all cohorts in the population to a single cohort, assumed to represent the stable age distribution of the population. Population size was based on an initial unfished spawning population, a declining exponential function for survival at age, and by the Baranov catch equation. The model assumed continuous recruitment, the magnitude of which was based on a Beverton-Holt stock-recruitment relationship. Fishing mortality (F) was stepped from zero to a specified upper limit while computing yield per recruit (YPR) and spawning biomass per recruit (SPR) for each value of F. The model was constructed as a QuattroPro for Windows (Version 5.0) spreadsheet.

The model required the following user supplied inputs:

1. An instantaneous rate of natural mortality (M)
2. A shape parameter value for the Beverton-Holt S-R relationship (A)
3. The unfished ("virgin") spawning biomass ($B0_s$) in kg (only required to scale absolute biomass)
4. The fishery selectivity coefficient at age (v)

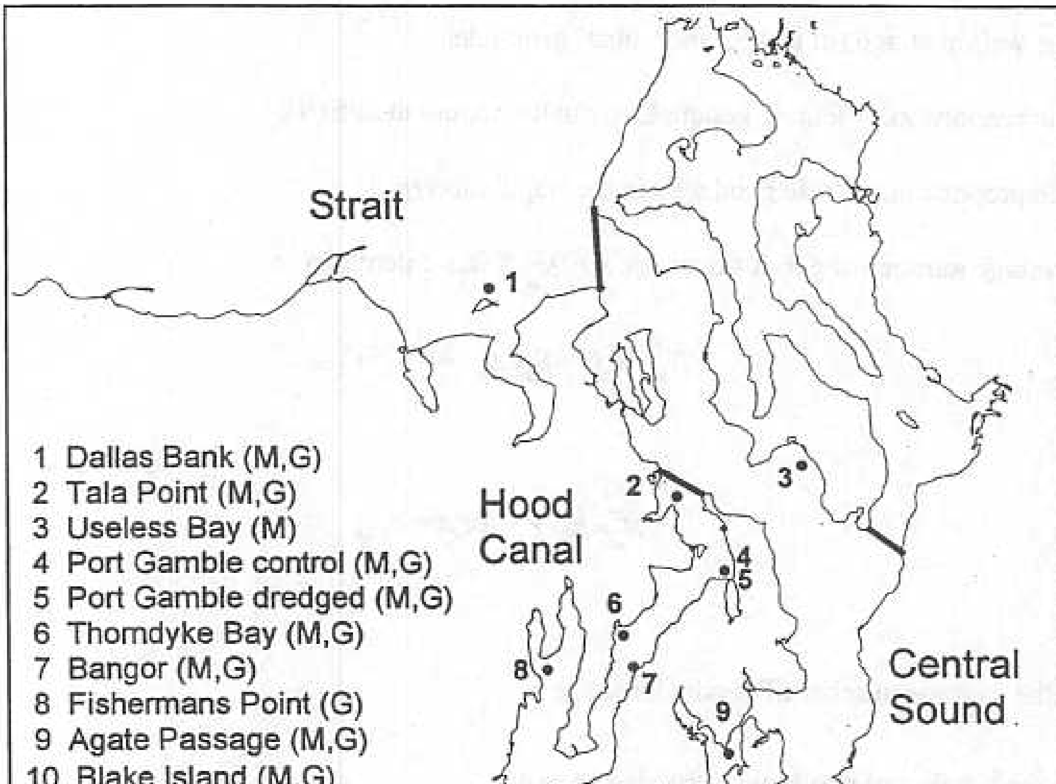


Figure 10. Sampling sites for geoduck natural mortality and growth.

5. The weight at age (in kg) for individual geoducks

6. The proportion of female geoducks sexually mature at age (Φ)

7. The proportion of male geoducks in the population (p_m)

The average number of geoducks at age a ($\overline{N_a}$) was calculated as

$$\overline{N_a} = N_a(1 - S_a)/Z_a \quad \text{for } a < a_{\max} \tag{1}$$

and

$$\overline{N_a} = N_a/Z_a \quad \text{for } a = a_{\max} \tag{2}$$

where

$\overline{N_a}$ = the average number of geoducks at age a

N_a = the number of geoducks surviving to age a

Z_a = the instantaneous rate of total mortality, $Z_a = M_a + v_a F$, or $= M_a + F_a$ where $F_a = F\, v_a$

M_a = the instantaneous rate of natural mortality at age a

F = the instantaneous rate of fishing mortality for fully selected age classes, i.e., $v_a = 1$

F_a = the instantaneous rate of fishing mortality at age a (= F v_a)

v_a = the selectivity coefficient at age a

S_a = the annual rate of survival, $S_a = \exp(-Z_a)$

$a_{\max}$ = the maximum modeled age of a geoduck in the population

The maximum age ($a_{\max}$) in the model served as an "accumulater age" category which encompassed all ages $a \geq a_{\max}$. The assumption implicit in this formulation is that no significant changes in growth, weight, maturity, or selectivity occurred beyond $a_{\max}$. In the case of geoducks, this assumption was reasonable and is addressed below. For other applications, the model spreadsheet could be simply extended to accommodate an unlimited number of older age classes.

For the first age class ($a = 1$), the number of geoducks surviving to age a (N_a) was calculated as

$$N_a = p_m \text{ for males} \tag{3}$$

and

$$N_a = 1 - p_m \text{ for females,} \tag{4}$$

where p_m was the proportion of males in the population.

For $a > 1$, the number of geoducks surviving to age a (N_a) was calculated as

$$N_a = N_{a-1} S_{a-1} \tag{5}$$

The average biomass (in kg) of geoducks at age a ($\overline{B_a}$) was calculated as

$$\overline{B_a} = \overline{N_a} w_a \tag{6}$$

where

w_a = the weight (in kg) of an individual geoduck at age a

Weight at age a was calculated from an allometric length-weight relationship of the form $w_a = xL_a^y$, where L_a = shell length (in cm) at age a, and x and y were constants. Length at age was based on the von Bertalanffy growth equation:

$$L_a = L_\infty [1 - \exp^{-k(a-t_0)}] \tag{7}$$

where L_a = shell length of a geoduck at age a, and L_∞, k, and t_0 were estimated parameters.

Yield per recruit (in kg) at age a (YPR_a) was calculated as:

$$YPR_a = \overline{B_a} (F v_a) = F \overline{B_a} v_a \tag{8}$$

Total yield per recruit (in kg) for all ages (YPR) was calculated as:

$$YPR = \sum_a \overline{B_a} (F v_a) = F \sum_a B_a v_a \tag{9}$$

Spawning weight per recruit (in kg) at age a (SPR_a) was calculated for females only as:

$$\mathrm{SPR}_a = \overline{B}_a \Phi_a \quad (10)$$

Total spawning weight per recruit (in kg) for all ages (SPR) was calculated as:

$$\mathrm{SPR} = \sum_a \overline{B}_a \Phi_a \quad (11)$$

The fraction of the unfished spawning stock biomass remaining at a given level of fishing mortality (P) was a parameter of the Beverton-Holt spawner-recruit relationship, such that

$$P = 1 - (1/A)\,(1 - \mathrm{SPR} / \mathrm{SPR0}) \quad (12)$$

where

A = the shape or "steepness" parameter of the Beverton-Holt spawner-recruit function, a user-supplied input ($0 \leq A \leq 1$)

SPR = total spawning weight per recruit (in kg) from equation 11 above

SPR0 = total spawning weight per recruit (in kg) from equation 11 above when F = 0 (i.e., unfished spawning weight per recruit)

Spawning biomass (B_s) in kg when F > 0 was calculated as:

$$B_s = P\,B0_s \quad (13)$$

where

P = the parameter in the Beverton-Holt S-R function which represents the fraction of the unfished spawning stock remaining at a given level of fishing mortality (see equation 12 above)

$B0_s$ = unfished spawning biomass in kg, a user-supplied input

Recruitment to the fishery (R) in numbers was calculated using the re-parameterized form (Kimura 1988) of the Beverton-Holt spawner-recruit relationship, such that

$$R = (B_s / \mathrm{SPR0}) / [1 - A\,(1 - P)] \quad (14)$$

where

B_s = spawning stock biomass in kg when F > 0 (equation 13 above)

SPR0 = unfished spawning weight per recruit in kg (i.e., when F = 0)

and A and P were parameters of the Beverton-Holt spawner-recruit function as described above.

Yield (Y) in kg was calculated as the product of total yield per recruit (in kg) and the number of recruits:

$$Y = YPR\,(R) \tag{15}$$

The model is capable of returning a suite of fishing mortality benchmarks, such as F_{max}, $F_{0.1}$, and $F_{xx\%}$. For example, the fishing mortality rate which produces, over the long run, the maximum yield per recruit corresponds to the F_{max} strategy, whereas $F_{0.1}$ represents a rate of harvest less than F_{max} (Deriso 1987, Gulland 1968).

The fraction of the unfished spawning weight per recruit remaining at a given level of fishing mortality was calculated as SPR/SPR0, and is achieved at a corresponding fishing mortality rate $F_{xx\%}$ where xx represents the ratio (SPR/SPR0)100. Model predictions of this fraction formed the basis for SPR-based fishing strategies. For example, the fishing mortality rate which resulted in a value of SPR/SPR0 = 0.35 corresponds to the $F_{35\%}$ strategy.

The harvest rate (μ) for fully selected age classes (i.e., when $v_a = 1$) when fishing and natural mortality operate concurrently (Ricker 1975) was calculated as:

$$\mu = F/Z\,[1-\exp(-Z)] \tag{16}$$

Parameter Estimates

Parameter estimates used in the equilibrium yield model are shown in Tables 4 and 5. The derivation of these parameter estimates is described below.

Table 4. Geoduck life history parameters held constant for all study sites.

Category	Parameter	Value
Spawning stock biomass when F = 0	$B0$,	100,000 kg
Instantaneous natural mortality rate	M	0.0226
Length-weight relationship	x	0.349127
	y	2.972807
Maturity (simple logistic)	x	-1.9
	y	9.5
Fishery selectivity (simple logistic)	x	-1.5
	y	8.0
Beverton-Holt shape parameter (Eq. 14)	A	1
Proportion of males in population	p_m	0.5
Maximum (accumulator) age	a_{max}	25

Natural Mortality

The instantaneous rate of natural mortality (*M*) was estimated from the geoduck age-frequency distribution at 14 of the 15 sample sites (Figure 10) using two different catch curve models (Robson and Chapman 1961; Ricker 1975). Both models assume that mortality is constant for all ages used in the catch curve. The Robson and Chapman model is based on a geometric distribution and assumes that year class survival and recruitment are constant and all ages are equally selected. Geoducks are extremely long-lived, so that the number of animals observed in each one-year age class is typically low, even for sample sizes in which $n > 1{,}000$. Despite this problem, we chose to preserve the data in one-year age classes rather than aggregating ages, a procedure which potentially ignores real variability in the original data and may slightly inflate estimates of *M* (Noakes 1992). It was not possible to estimate site-by-site mortality rates using catch curves, because no individual site contained enough data to construct reliable catch curves. Age frequencies were therefore pooled from all 14 sites in order to create the catch curve.

To avoid arbitrary choices of the upper and lower ages used in the catch curve "right limb," we established a protocol for data inclusion: The initial upper age limit for the catch curve was the first age at which our sample contained no geoducks (i.e., the first gap in frequency). We then excluded younger age frequencies if they were identified as outliers by Weisberg's (1985) outlier test. Two methods were used to select the lower age limit for the catch curve: 1) The chi-square procedure described in Robson and Chapman (1961) was used to differentiate partially selected ages; and 2) Catch curve regressions were calculated for all possible lower age limits, and we used an *ad hoc* procedure to optimize the coefficient of determination (r^2) and the linearity of positive and negative residuals plotted against age. Once the lower and upper age limits for the catch curve were identified, a chi-square formula was then used to test goodness of fit of fully-selected ages to a geometric distribution (i.e., the Robson and Chapman model).

Sampled geoducks from the 14 previously-unfished sites ranged in age from 2 to 131 years (Figure 11A). The mean age of geoducks was 46 years ($SE = 0.56$, $n = 2{,}157$). The initial upper age limit for the catch curve was 110 years, because no 111-year old geoducks were in our sample. Examination of residuals showed a single large negative residual at the 99-year age class (only one geoduck of this age was in our sample), and this age class was eliminated from the analysis as an outlier, based on the test given in Weisberg (1985). Both the Robson and Chapman (1961) chi-square procedure and our *ad hoc* optimization procedure identified age 28 as the lower age limit for the catch curve. A chi-square was used to test goodness of fit of fully-selected ages (28-98) to a geometric distribution. The resulting chi-square was highly significant ($\chi 2 = 326.56$, $df = 68$), indicating that the age frequency was not geometric in distribution, and that data requirements for the Robson and Chapman model were not met. Ricker (1975) pointed out that in most stocks, difference in year class strength is the major source of variability, in which case the best estimate of survival would be obtained from a catch curve analysis with equal weighting. The Ricker catch curve based on ages 28 - 98 (Figure 11B) produced an estimate of $M = 0.0226\ y^{-1}$ ($\pm$ 0.0018 SE, $n = 71$, $r^2 = 0.70$).

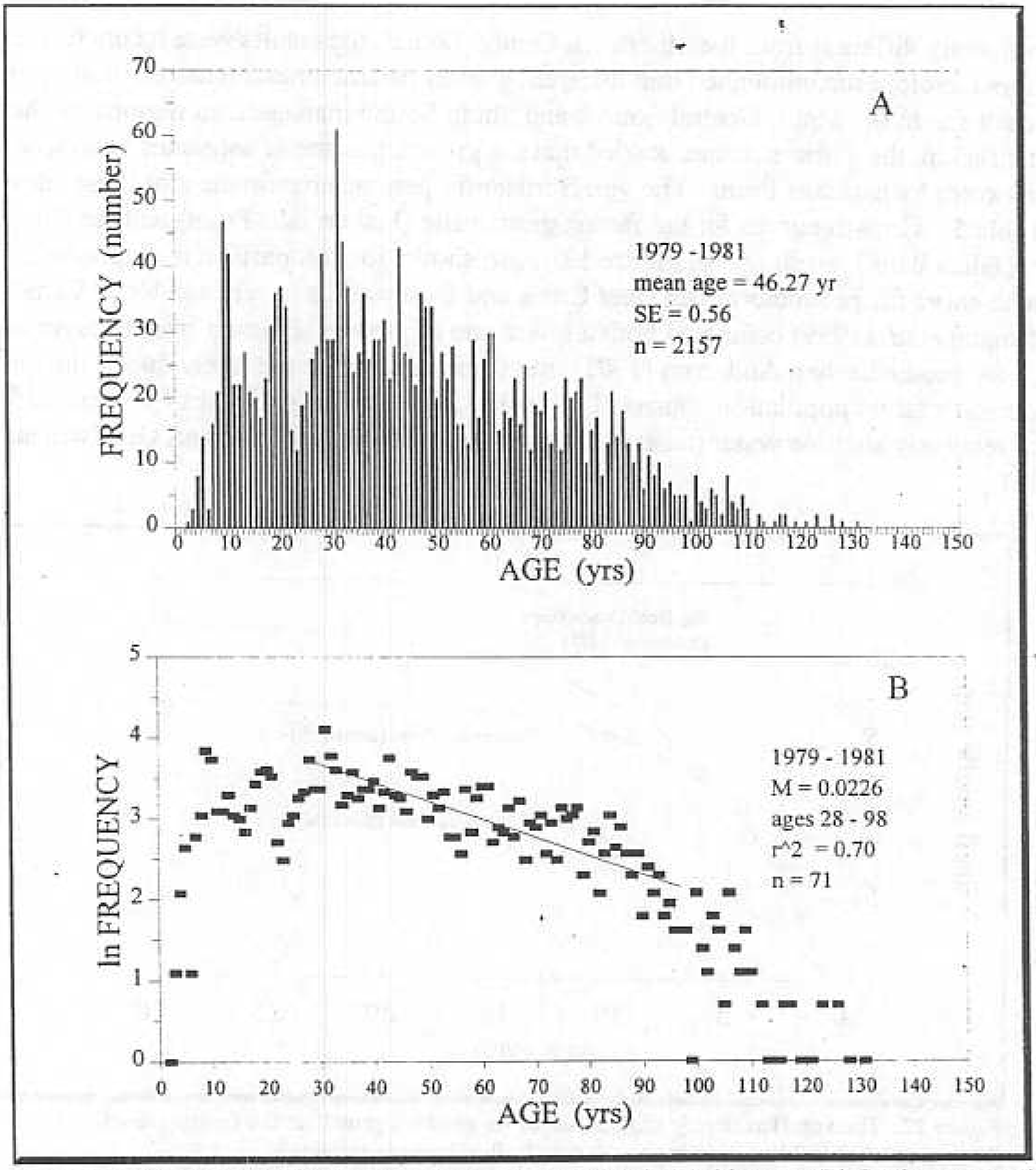


Figure 11. (A) Age frequency geoducks sampled at 14 sites in Washington. (B) Catch curve used to estimate the instantaneous natural mortality rate (*M*) for geoducks.

Growth

Of the three von Bertalanffy growth parameters, only one significantly influenced model-derived target fishing mortality rates: the growth constant *k* (Hoffmann *et al.* 1999). Statistically significant differences in *k* were detected among most of the sites within 3 management regions: Central Sound, Hood Canal, and South Sound. Further testing showed that in South Sound, the sites were also significantly different. In Hood Canal, only one site (Fishermans Point) was significantly different from the others. In Central Sound, the results were inconclusive. The authors therefore recommended that different growth parameter estimates be used as model input for each site in the Strait, Central Sound, and South Sound management regions; in the Hood Canal region, the authors recommended that the growth parameter estimates be averaged for all sites except Fishermans Point. The von Bertalanffy parameter estimates for these sites are shown in Table 5 . Growth curves for the fastest growth site (Fishermans Point) and the slowest growth site (Dallas Bank) are shown in Figure 12. Also shown for comparison is Anderson's (1971) growth curve for geoducks at Big Beef Creek and Dosewallips beaches in Hood Canal. Hoffmann *et al.* (1999) estimated both a lower rate of growth (k) and a smaller asymptotic size (L_∞) for geoducks than Anderson (1971), but these differences are likely due to the fact that Anderson's target population consisted of young, fast-growing geoducks (<5 years old) sampled from relatively shallow water (where mean geoduck shell length is larger; Goodwin and Pease 1991).

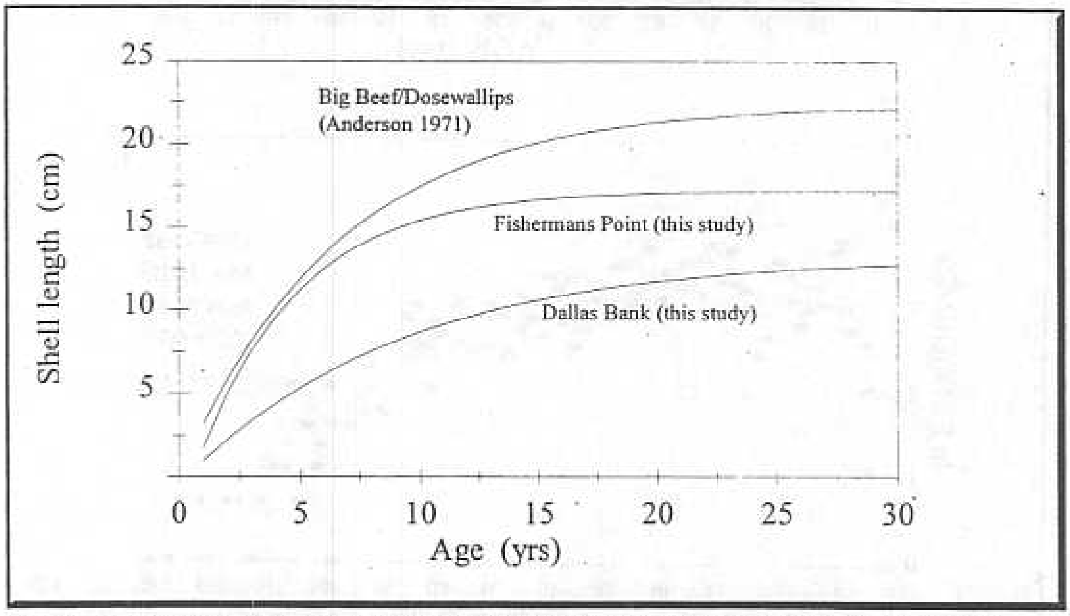


Figure 12. The von Bertalanffy growth curves for geoduck growth at the fastest growth site (Fishermans Pt.) and the slowest growth site (Dallas Bank) in this study.

Length-weight Relationship

Goodwin (1976) calculated an allometric length-weight relationship for Washington geoducks in log-log form. We converted this to the more familiar power curve form $w_a = xL_a^y$, where w_a = weight (in g) at age a, L_a = shell length (in cm) at age a (Table 4).

Sex Ratio

The proportion of males (p_m) in the geoduck population was set to $p_m = 0.5$ based on a 50:50 sex ratio for geoducks older than 10 years (Goodwin and Pease 1989).

Maturity

The proportion of sexually mature geoducks at age was estimated by fitting a simple logistic curve to maturity data from published sources. Anderson (1971) found that 50% of his sample of geoducks was mature at 75 mm and an age that he estimated to be 3 years. The Washington growth curves described above suggest that this length would be attained in roughly 5 years, depending on the site. Sloan and Robinson (1984) reported that geoducks mature at 5 years and reproduce for at least a 100-year period with no "reproductive senility." They stated that "unequivocally mature geoducks" were 6 to 103 years old (late-active males) and 12 to 95 years old (late-active females). Based on these two sources, we fit a logistic curve with the least squares method and two data points, whereby 50% of the female geoducks would mature at 5 years and 100% by 12 years. The proportion of mature geoducks (Φ) at age a is described by

$$\Phi_a = 1/(1 + \exp^{xa+y}) \tag{17}$$

where a is age in years, $x = -1.9$, and $y = 9.5$.

Fishery Selectivity

Fishery selectivity at age was based loosely on Harbo *et al.* (1983), who reported that recruitment to the British Columbia geoduck fishery begins at 4 years and is complete by 12 years. We fit a simple logistic curve using the least squares method and two data points, assuming geoducks enter the fishery at roughly 4 years and, to more conservatively model fishery selectivity, assume that geoducks are fully selected by 8 years.

$$v_a = 1/(1 + \exp^{xa+y}) \tag{18}$$

where v_a is the proportion of geoducks of age a selected by the fishery, a is age in years, $x = -1.5$, and $y = 8$.

Stock-recruit Relationship

Nothing is known about the form or steepness of the stock-recruit (S-R) relationship for geoducks. We therefore set the Beverton-Holt shape parameter (A) equal to 1.0 for all model runs. In other words, we assumed that recruitment was independent of spawning stock abundance. This assumption is reviewed below in *Discussion*.

Maximum Age

As a practical convenience, the equilibrium yield model uses an "accumulater age" category (a_{max}) as the final age category, encompassing all ages $a \geq a_{max}$. For this study, we set $a_{max} = 25$, which implicity assumes that there are no significant changes in growth, selectivity, or maturity beyond age 24. This assumption is reasonable for geoducks, which reach asymptotic size between the ages of 10-20 years (Hoffmann *et al.* 1999).

Results

Fishing Mortality Rates for Five Harvest Strategies

We ran the model for each site, varying only the growth parameters based on the analysis of growth presented in Hoffmann *et al.* (1999). The only sites where growth parameter estimates (specifically, the growth constant *k*) could be pooled were five of the six Hood Canal sites. In all other cases, site-specific growth parameters could not be pooled, and therefore separate model outputs were calculated for each site. All inputs except growth parameters were identical for each model run (Table 1). Growth parameters used as site-specific input are shown in Table 5.

Table 5. Bench mark instantaneous fishing mortality rates for fully-selected geoducks ($v_a = 1.0$) from seven sites in Washington. Model inputs except growth parameters are from Table 4. Growth parameter estimates are from Hoffmann *et al.* (1999).

Region	Site	n (sites)	L_∞ (cm)	k	t_0	F_{max}	$F_{0.1}$	$F_{35\%}$	$F_{40\%}$	$F_{50\%}$
South Sound	Hunter Point	1	16.4	0.23	0.72	0.090	0.036	0.036	0.029	0.020
	Herron Island	1	13.2	0.15	0.42	0.064	0.031	0.032	0.027	0.018
Central Sound	Agate Passage	1	15.8	0.20	0.18	0.085	0.035	0.035	0.029	0.020
	Blake Island	1	14.6	0.16	0.81	0.064	0.031	0.032	0.027	0.019
Hood Canal	Five sites pooled	5	12.8	0.16	0.47	0.067	0.032	0.033	0.027	0.019
	Fishermans Point	1	16.8	0.24	0.55	0.100	0.037	0.036	0.030	0.020
Strait	Dallas Bank	1	12.0	0.11	0.33	0.053	0.028	0.030	0.025	0.018

Values of the instantaneous fishing mortality rate (F) for five commonly-used constant harvest rate strategies are shown in Table 5. F_{max} is the fishing mortality rate that produces, over the long run, the maximum yield per recruit (YPR). $F_{0.1}$ is a common alternative to F_{max}, and is the rate of fishing mortality at which the marginal YPR is 10% of the marginal YPR for a lightly exploited fishery (Deriso 1987). $F_{35\%}$, $F_{40\%}$ and $F_{50\%}$ are spawning biomass per recruit (SPR) based harvest rates which reduce SPR to either 35%, 40% or 50% of the unfished level (Clark 1991).

F_{max} ranged from 0.053 to 0.100 depending on the site (Table 5). These rates correspond to annual harvest rates (μ) of 5.1 - 9.4% of the exploitable geoduck biomass. The Strait of Juan de Fuca region, represented by the single sampling site at Dallas Bank, produced the lowest value, while Fishermans Point in Hood Canal produced the highest value. The F_{max} strategy reduced SPR to 15-21% of the unfished level, depending on the site. Values for $F_{0.1}$ ranged from 0.028 to 0.037, corresponding to annual harvest rates of 2.7 - 3.6%. This strategy reduced SPR to 35-37% of the unfished level, depending on the site.

Values for $F_{35\%}$ were, predictably, nearly identical to the $F_{0.1}$ rates, ranging from 0.30 - 0.36 (μ = 2.9 - 3.5%). F values for the $F_{40\%}$ strategy ranged from 0.025 - 0.030 (μ = 2.4 - 2.8%). The mean F value for the $F_{40\%}$ strategy was 0.028, corresponding to μ = 2.7%. F values for the $F_{50\%}$ strategy ranged from 0.018 - 0.020 (μ = 1.8 - 2.0%).

Model Sensitivity to Parameter Estimates

All the parameter estimates used to drive the model are subject to varying degrees of uncertainty. It is therefore reasonable to ask what might happen to our predictions if the true values of M or k, for example, were much lower or higher than our estimates. We tested the sensitivity of the model by running it with a range of values for each parameter in turn, while holding all other parameters constant. Values ranging from one-tenth the "best" parameter estimate (from Tables 4 and 5) to three times the estimated value were used in the analysis. Only the fishing mortality rates corresponding to the $F_{40\%}$ strategy were calculated, but the trend for other strategies would be similar.

The model was most sensitive to the estimate of M, with $F_{40\%}$ values ranging from 0.003 to 0.068 as M was increased from one tenth to three times our "best" estimate of M = 0.0226 (Figure 13). The model was far less sensitive to the other parameter estimates, as evidenced by the relatively flat $F_{40\%}$ trajectories for values of the growth coefficient k, the selectivity constant y, and the maturity constant y. For example, varying the value of k from one-tenth to three times our "best" estimate resulted in $F_{40\%}$ values which ranged only from 0.021 to 0.033.

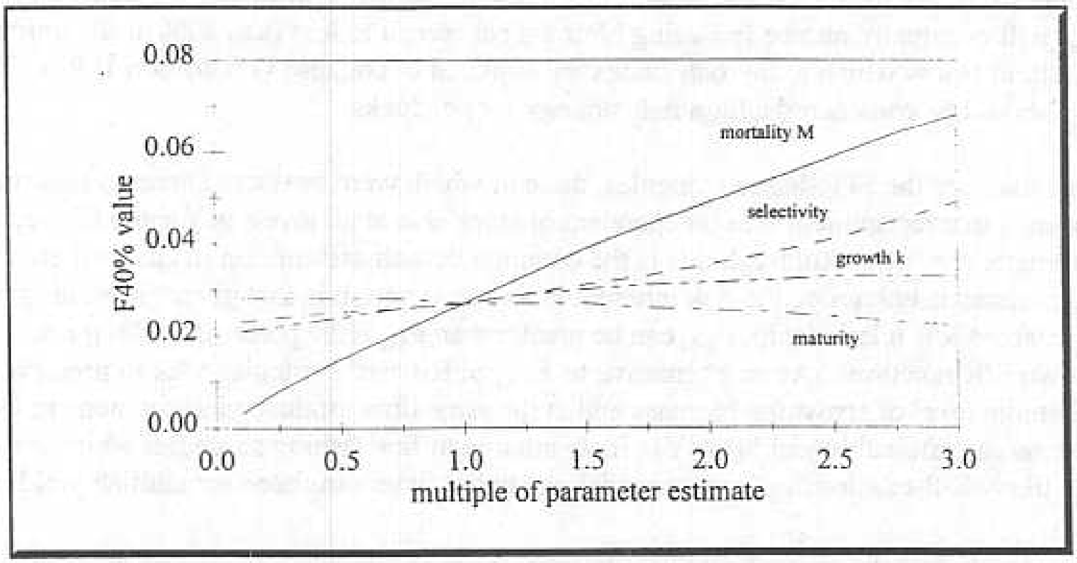


Figure 13. The effect of different parameter estimates on model-derived F $_{40\%}$ values.

Discussion

Our primary objective in equilibrium modeling was to simulate the long-term results of various geoduck fishing strategies, both in terms of yield and spawning biomass per recruit. Before discussing our results, it is perhaps necessary to explain why we attach such importance to geoduck harvest rate strategies, particularly since the differences between many of the modeled options may appear trivial.

In many fisheries, especially those in which biomass is small or estimated with great uncertainty, debating a 1% difference between annual harvest rate options would indeed be trivial. But in Washington's geoduck fishery, where the exploitable biomass is large (73,843 t in 1999; Sizemore and Ulrich 1999) and the price is high, even tiny incremental differences in the recommended harvest rate have tremendous economic significance. Moreover, because geoducks have a low M (and presumably a low intrinsic rate of increase), small differences in annual harvest rates can have profound cumulative effects on stock size, especially if the harvest rate is set too high. This is not to discount the importance of good biomass estimates, but we believe there are several reasons why Washington managers should place the greatest emphasis on improved harvest rate strategies rather than improved biomass estimates. First, biomass estimates for individual geoduck beds in Washington have coefficients of variation (CV) averaging about 20%. Simulation tests suggest that biomass estimation errors of this magnitude are unlikely to result in substantial degradation of long-term harvest performance (Frederick and Peterman 1995). Second, even greatly increased sampling is not likely to improve biomass estimate CVs very much. Third and most importantly, errors in biomass estimation are assumed to be reasonably unbiased. An error in setting the annual harvest rate, on the other hand, will have a persistent and cumulative effect on stocks in only one direction, either underharvest or overharvest. We therefore believe that, given reasonable estimates of stock size, choosing a harvest strategy remains the most critical aspect of geoduck management.

In this study, we evaluated five common harvest strategies. Our model predicts that fishing at F_{max} will eventually reduce spawning biomass per recruit to less than 20% of the unfished level, a threshold below which many fish stocks are assumed to collapse (Thompson 1993). Therefore, F_{max} should be considered a high risk strategy for geoducks.

Less risky are the SPR-based strategies, three of which were evaluated here. In this study, we assumed that recruitment was independent of stock size at all levels of fishing (Beverton-Holt parameter A = 1.0). Although this is the common default assumption in cases where the S-R relationship is unknown, the risk inherent in this assumption is that given an existing but undetected S/R relationship, $F_{x\%}$ can be greater than F_{MSY} (the preferred fishing rate with a known S/R function). As an alternative to F_{max}, SPR-based strategies seek to preserve some minimum level of spawning biomass and at the same time produce yields which are close to the maximum sustainable yield (MSY). In an attempt to find fishing strategies which are robust for any likely S-R relationship, recent modeling studies have simulated groundfish yields using a range of typical life history parameters and realistic S-R models. Clark (1991) showed that fishing at $F_{35\%}$ would achieve at least 75% of MSY for a wide range of deterministic S-R relationships. On the basis of his results, $F_{35\%}$ has been adopted as a target rate for a number of fish stocks in Alaska and the U.S. Pacific coast. Clark (1993) later revised his recommendation to $F_{40\%}$ after considering variability in recruitment, but remarked that "it would be silly to argue very hard for or against any specific rate between $F_{35\%}$ and $F_{45\%}$." Mace (1994) also recommended $F_{40\%}$, which she claimed was a modest improvement over $F_{35\%}$. She states that $F_{40\%}$ represents a risk-averse fishing strategy in the common situation where there is adequate information to place bounds on all relevant life history parameters except the S-R relationship. Quinn and Szarzi (1993) modeled clam fisheries in Alaska and recommended SPR-based strategies equivalent to a range of $F_{30\%}$ to $F_{45\%}$.

On the basis of the results presented here, state and Tribal geoduck managers formally agreed on December 5, 1997 to an $F_{40\%}$ strategy for geoducks, applying an instantaneous fishing mortality rate of $F = 0.028$; the corresponding annual harvest rate for fully selected age classes (μ) is 0.027, or 2.7% of the exploitable biomass (*Appendix A* to state/Tribal geoduck agreements). Annual fishing quotas within each of the six management regions are calculated as the product of this harvest rate and the estimated exploitable biomass within the region (available from dive survey data). British Columbia managers calculate annual quotas using a fixed harvest rate of 1% (Campbell *et al.* 1998), but until recently this rate was applied to the estimated *virgin* biomass rather than current biomass estimates as is done in Washington.

Suggestions for Future Research

A secondary objective of our study was to determine which of the estimated geoduck life history parameters were most influential in predictions of yield and spawning biomass per recruit. The model was most sensitive to the estimate of natural mortality (M), while growth, selectivity, and maturity parameters had relatively little effect on SPR-based fishing mortality rates. This suggests that future research monies are best spent making more reliable estimates of M.

Our estimate of $M = 0.0226$ is similar to estimates from British Columbia. Sloan and Robinson (1984) estimated $M = 0.035$ at a single site, while Breen and Shields (1983) reported $M = 0.01$ to 0.04 in five populations. Noakes (1992) estimated $M = 0.03$ to 0.04 at three sites. Both our estimate and the British Columbia estimates relied on the catch curve method, which assumes that mortality rate is uniform with age and that recruitment has been constant over the range of age-groups analyzed. There is some suggestion in our age-frequency data that a shift in geoduck recruitment has occurred which could have biased the estimate of M. Age frequencies did not begin to decline until about age 25, a pattern in catch curves which is often due to inefficient sampling of younger age classes. But for geoducks, which grow quickly and are fully selected by the commercial fishery at half this age (Harbo *et al.* 1983), sampling inefficiency is not a plausible explanation for the low numbers of geoducks in the 10-25 year age group. Instead, low numbers of 10 - 25 year-old geoducks may indicate poor recruitment during the 15-year period prior to sampling. This suggests that recruitment declined during the period 1955-1970 (prior to the advent of a fishery), and perhaps more recently. Sloan and Robinson (1984) suggested the possibility of a similar decline in recruitment during the same time period in British Columbia.

Thus, catch curve estimates of *M* for geoducks based on older age classes may not accurately represent current trends in natural mortality. They likewise reveal nothing about *M* for younger geoducks. In either case, our results indicate that biases in the estimate of *M* will have a major influence on model-based predictions of yield and spawning biomass per recruit. Independent estimates of *M* should therefore be a high priority for research.

Given the fact that geoducks are entirely sedentary, direct estimates of *M* for adult geoducks are possible using non-invasive tags. In 1998 WDFW began testing a tagging method for estimating *M* at a previously unfished site in northern Hood Canal. Divers "tagged" 1,128 adult geoducks (>3-4 yrs) in May 1998 by placing thin plastic stakes next to geoduck siphons at a distance of 3 inches. Geoducks were tagged within 3 ft of three lines running offshore and anchored in depths of -18 m to -70 ft MLLW. One year later, we found 875 of the original 1,128 tags remaining in the substrate. Over a 6-day period, siphons were visible next to 856 of the tags. We used a venturi dredge to excavate the 19 tags with no visible siphons; 4 of these geoducks were alive, 14 were dead, and one tag had no sign of a living or dead geoduck. The annual survival rate (*S*) for all three lines was estimated as $N_1 / N_0 = 861/875 = 0.984\ y^{-1}$ (95% CI = 0.991 - 0.973) and the corresponding estimate of *M* was $0.016\ y^{-1}$. Estimates of *S* on individual lines ranged from 0.996 to 0.0.970, suggesting that survival and mortality rates vary widely even over small spatial scales. The direct estimate of *M* makes fewer assumptions than catch curve estimates and is less expensive. Now that the tagging method has proved feasible, experiments to estimate *M* at sites throughout Washington are recommended.

Although the model was not nearly as sensitive to growth parameter estimates as it was to *M*, Hoffmann *et al.* (1999) found evidence for site-specific differences in the growth parameter *k* which were of "managerial significance" (i.e., of a magnitude to influence model-derived target fishing mortality rates). However, since the growth sample sites were not selected at random, regional estimates of *k* which are simply averages of the estimated site *k*'s will be biased. One solution, albeit a costly one, is to collect additional growth samples from a number of randomly-selected sites in all regions. Another possible solution is to analyze the empirical relationship between mean shell length at sites and the site-specific estimate of *k*; preliminary studies suggest that there is a positive linear relationship between the two. If this relationship proves significant, the huge volume of existing shell length data gathered every year since 1968 during pre-fishing surveys could be parsed by management region to obtain regional estimates of mean shell length. These could then be compared statistically and used to calculate empirical estimates of *k* for each region. This approach, if feasible, would not require any additional field work, but would instead rely on the large and already-existing morphological database for geoducks.

Finally, we plan to continue the empirical "recovery" study on at least 15 previously fished geoduck beds. This study tracks changes in geoduck density before fishing, immediately after fishing, and then at intervals following fishing. A recovery rate for each tract is estimated from the difference in density between the first post-harvest survey and the second post-harvest survey. The study is expected to provide empirical estimates of the time required for geoduck density to return to pre-fishing levels. Thus far, three surveys have been completed at all the sites: a survey prior to fishing, a survey immediately after harvest, and a second post-harvest survey. The decrease in geoduck density immediately after fishing averaged 72% and ranged from a low of 19% to a high of 95%. The elapsed time between the first and second post-harvest surveys ranged from 4 to 11 years, averaging 8 years. During this period following fishing, density increased on all the tracts. The average estimated time to recover to pre-fishing density (assuming 100% removal of all geoducks and linear recovery) was 39 years, ranging from a low of 11 years to a high of 73 years. Thus, the proportion of fished biomass replaced each year on average was 1/39 = 0.0256. A simple biomass dynamics model was used to compare the average recovery time estimated thus far (39 years) with the existing annual harvest rate of 2.7%. The model predicted that a recovery time of 39 years and fishing at 2.7% every year eventually reduced biomass to 49% of its unfished level. Since this is greater than the 40% target level for the $F_{40\%}$ strategy, the current harvest rate of 2.7% is considered conservative. However, the study must be continued at intervals to better define the shape of the recovery curve and the time required for recovery.

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Appendix 1
Geoduck Survey Data Sheets

✓PREFISHING
__POST FISHING
__OTHER______

DIG ___

REFERENCE: 99207

GEODUCK TRANSECT (900 ft.²) DATA SHEET

LOCATION: PILOT POINT REGION CODE CS TRACT CODE 06200

STATION: 87 DATE: 4/28/99 Chart Datum NAD 27

START TIME: 1041 DEPTH CORRECTION: {+1.6}

DGPS POSITION: LATITUDE: 4752962 LONGITUDE: 12230611

UNCORRECTED BEG. DEPTH: 48 ft. CORRECTED BEG. DEPTH: 46 ft.

UNCORRECTED END DEPTH: 26 ft. CORRECTED END DEPTH: 24 ft.

GEODUCK COUNT 1: 7 GEODUCK COUNT 2: 20

SHOW FACTOR: 0.75

ADULT CUCS: 4 JUVENILE CUCS: 0

SUBSTRATE RATING: Mud 1 Sand 2 Peagravel___ Gravel___ Shell___ Cobble___

Boulder___ Unstable______ Other wood debris

P1: 6 P2: 7 P3:___ P4:___ P5:___ P6:___ P7:___ P8:___ P9:___ P10:___ P11:___ P12:___

A1: 1 A2: 18 A3: 26 A4: 28 A5: 29 A6: 4 A7:___ A8:___ A9:___ A10:___ A11:___ A12:___

A13:___ A14:___ A15:___ OTHER:______

DIVER NAME(s) AB BS BOTTOM TIME 36 min.

FROM BUOY # 36 TRANSECT LINE 82 → 87

COMPASS COURSE 270° MAGNETIC

ADDITIONAL COMMENTS:

END @: 1117

DGPS 47°52971'

122°30641'

Enter ☑ E.C. ☑

GEODUCK WATER-JET HARVEST DATA

REFERENCE: 99052

REGION: CS TRACT CODE: 06200 STATION: 52 DATE: 4/21/99

START TIME: 1048 DEPTH CORRECTION: +8.2

DGPS POSITION: LATITUDE: 4753083 LONGITUDE: 12230646

UNCORRECTED BEG. DEPTH: 56 ft. CORRECTED BEG. DEPTH: 48 ft.

UNCORRECTED END DEPTH: 57 ft. CORRECTED END DEPTH: 49 ft.

SUBSTRATE RATING: Mud 1 Sand 1 Peagravel___ Gravel___ Shell___ Cobble___

Boulder___ Other:___

DIFFICULTY: 1 ABUNDANCE: 2 DEPTH: 1 COMPACT: 0 GRAVEL: 0 SHELL: 1

TURBIDITY: 0 ALGAE: 0 COMMERCIAL: Y NUMBER DUG: 10

NO GUT SHOT!

TIME TAKEN TO DIG GEODUCKS: 5 (minutes) NUMBER GEODUCK > 907 (g) 6

DIVER NAME(s) AB BOTTOM TIME 14 min.

	VALVE LENGTH[1] (mm)	WHOLE WEIGHT (g)	SIPHON WEIGHT (g)	GS[2]	BV[3]	COMMERCIAL QUALITY (y/n)	COMMENTS
1.	136	1035	205				
2.	125	1027	270				
3.	137	1135	294				
4.	123	656	169				
5.	122	857	229				
6.	167 LV	1170	269				
7.	106 LV	345	107		✓RV		WATER LOSS
8.	137	1015	242				
9.	125	495	103				
10.	155	1051	191				
11.							
12.							
13.							

[1]LENGTH = RIGHT VALVE WHEN NOT BROKEN
[2]GS = GUT SHOT (WATER LOSS)
[3]BV=BROKEN VALVE

e:\forms\geoduck.frm last update 5/18/98

Enter ☑ E.C. ☑

Appendix 2
Geoduck Data Sheet Codes

Geoduck Survey Animals List - number organized

Last updated: 11/10/99

	Taxonomer	Common Name	Group	Phylum
0	*Elzippo nullus*	NO ANIMALS	ENTROPY	KARMA
1	*Butter, littleneck, venus'*	HARDSHELL CLAM	BIVALVE	MOLLUSC
2	*Tresus spp.*	HORSE CLAM	BIVALVE	MOLLUSC
3	*Ptilosarcus gurneyi*	SEA PEN	MISC.	COELENTERATE
4	*Parastichopus californicus*	SEA CUCUMBER	CUCUMBER	ECHINODERM
5	*Unspecified*	GHOST SHRIMP	SHRIMP	ARTHROPOD
6	*Cancer magister*	DUNGENESS CRAB	CRAB	ARTHROPOD
7	*Cancer productus*	RED ROCK CRAB	CRAB	ARTHROPOD
8	*Cancer gracilis*	GRACEFUL CRAB	CRAB	ARTHROPOD
9	*Strongylocentrotus*	SEA URCHIN	URCHIN	ECHINODERM
10	*Mya truncata*	TRUNCATED MYA	BIVALVE	MOLLUSC
11	*Unspecified Pectinid*	SCALLOP	BIVALVE	MOLLUSC
12	*Chaetopterid polychaete tubes*	ROOTS	MISC.	ANNELID
13	*Unspecified Pholadid*	PIDDOCK	BIVALVE	MOLLUSC
14	*Panomya beringiana*	FALSE GEODUCK	BIVALVE	MOLLUSC
15	*Unspecified*	ANEMONE	ANEMONE	CNIDARIA
16	*Polinices lewisi*	MOON SNAIL	GASTROPOD	MOLLUSC
17	*Stylatula elongata*	SEA WHIP	MISC.	COELENTERATE
18	*Pycnopodia helianthoides*	SUNFLOWER STAR	SEA STAR	ECHINODERM
19	*Unspecified*	NUDIBRANCH	MISC.	MOLLUSC
20	*Unspecified*	HERMIT CRAB	CRAB	ARTHROPOD
21	*Luidia foliolata*	SAND STAR	SEA STAR	ECHINODERM
22	*Pisaster brevispinus*	SHORT-SPINED STAR	SEA STAR	ECHINODERM
23	*Evasterias troschelli*	FALSE OCHRE STAR	SEA STAR	ECHINODERM
24	*Loligo opalescens*	SQUID EGGS	CEPHALOPOD	MOLLUSC
25	*Polinices lewisii*	MOON SNAIL EGGS	GASTROPOD	MOLLUSC
26	*Unspecified*	FLATFISH	FISH	CHORDATE
27	*Dendraster excentricus*	SAND DOLLAR	SEA BISCUIT	ECHINODERM
28	*Modiolus rectus*	HORSE MUSSEL	BIVALVE	MOLLUSC
29	*Henricia leviuscula*	BLOOD STAR	SEA STAR	ECHINODERM
30	*Unspecified Raja*	SKATE	FISH	CHORDATE
31	*Pachycerianthus fimbriatus*	BURROWING ANEMONE	ANEMONE	CNIDARIA
32	*Metridium senile*	PLUMED ANEMONE	ANEMONE	CNIDARIA
33	*Dermasterias imbricata*	LEATHER STAR	SEA STAR	ECHINODERM
34	*Hydrolagus colliei*	RATFISH	FISH	CHORDATE
35	*Unspecified cottid*	SCULPIN	FISH	CHORDATE
36	*Unspecified*	BURROWING CUCUMBER	CUCUMBER	ECHINODERM
37	*Nassarius spp.*	BASKET SNAIL	GASTROPOD	MOLLUSC
38	*Anarrhichthys ocellatus*	WOLF EEL	FISH	CHORDATE
39	*Unspecified*	STARFISH	SEA STAR	ECHINODERM
40	*Sebastes spp.*	COLORED ROCKFISH	FISH	CHORDATE
41	*Sebastes melanops*	BLACK ROCKFISH	FISH	CHORDATE
42	*Hexagrammos sp.*	GREENLING	FISH	CHORDATE
43	*Ophiodon elongatus*	LINGCOD	FISH	CHORDATE
44	*S. fransiscanus*	RED URCHIN	URCHIN	ECHINODERM
45	*S. purpuratus*	PURPLE URCHIN	URCHIN	ECHINODERM
46	*S. droebachiensis*	GREEN URCHIN	URCHIN	ECHINODERM
47	*Anthopleura xanthogrammica*	LARGE GREEN ANEMONE	ANEMONE	CNIDARIA
48	*Unspecified*	MYSIDS	MISC.	ARTHROPOD
49	*Pisaster ochraceus*	OCHRE STAR	SEA STAR	ECHINODERM
50	*Scorpaenichthys marmoratus*	CABEZON	FISH	CHORDATE
51	*Crassadoma gigantea*	ROCK SCALLOP	BIVALVE	MOLLUSC
52	*Eschrictious robustus*	GREY WHALE	MAMMAL	CHORDATE
53	*Haliotis kamtschatkana*	ABALONE	GASTROPOD	MOLLUSC
54	*Ammodytes hexapterus*	SAND LANCE	FISH	CHORDATE
55	*Unspecified embiotocid*	PERCH	FISH	CHORDATE
56	*Solaster spp.*	SUN STAR	SEA STAR	ECHINODERM
57	*Octopus spp.*	OCTOPUS	MISC.	MOLLUSC
58	*Balanus nubilis*	GIANT BARNACLE	MISC.	ARTHROPOD
59	*Cryptochiton stelleri*	GUMBOOT CHITON	MISC.	MOLLUSC
60	*Chlamys rubida, C. hastata.*	SINGING SCALLOPS	BIVALVE	MOLLUSC
61	*Fusitriton oregonensis*	OREGON TRITON	GASTROPOD	MOLLUSC
62	*Unspecified*	GOBIE	FISH	CHORDATE

63 *Orcus orcinus*	KILLER WHALE	MAMMAL	CHORDATE
64 *Panopea abrupta*	GEODUCK	BIVALVE	MOLLUSC
65 *Telmessus cheiragonus*	HELMET CRAB	CRAB	ARTHROPOD
66 *Squalus acanthias*	DOGFISH SHARK	FISH	CHORDATE
67 *Mytilus californianus*	CALIFORNIA MUSSEL	BIVALVE	MOLLUSC
68 *Stylasterias forreri*	FISH-EATING STAR	SEA STAR	ECHINODERM
69 *Clupea harengus pallasi*	HERRING	FISH	CHORDATE
70 *Syngnathus leptorhynchus*	PIPEFISH	FISH	CHORDATE
71 *Unspecified serpulid*	TUBE WORM	MISC.	ANNELID
72 *Raja spp.*	SKATE EGGS	FISH EGGS	CHORDATE
73 *Unspecified*	ASSORTED SHRIMP	SHRIMP	ARTHROPOD
74 *Clinocardium nuttalli*	COCKLE	BIVALVE	MOLLUSC
75 *Unspecified agonid*	POACHER	FISH	CHORDATE
76 *Poraniopsis inflata*	SPINY STAR	SEA STAR	ECHINODERM
77 *Crossaster papposus*	ROSE STAR	SEA STAR	ECHINODERM
78 *Mediaster aequalis*	VERMILLION STAR	SEA STAR	ECHINODERM
79 *Oncorhynchus spp.*	SALMON	FISH	CHORDATE
80 *Gadus macrocephalus*	PACIFIC COD	FISH	CHORDATE
81 *Cucumaria miniata*	ORANGE CUCUMBER	CUCUMBER	ECHINODERM
82 *Eupentacta quinquesemita*	WHITE CUCUMBER	CUCUMBER	ECHINODERM
83 *Urticina sp.*	STRIPED ANEMONE	ANEMONE	CNIDARIA
84 *Unspecified holothurian*	BLACK CUCUMBER	CUCUMBER	ECHINODERM
85 *Gorgonocephalus euchemis*	BASKET STAR	SEA STAR	ECHINODERM
86 *Orthasterias koehleri*	RAINBOW STAR	SEA STAR	ECHINODERM
87 *Lopholithodes mandti*	BOX CRAB	CRAB	ARTHROPOD
88 *Unspecified Porifera*	LARGE SPONGES	MISC.	PORIFERA
89 *Diadora spera*	KEYHOLE LIMPET	GASTROPOD	MOLLUSC
90 *Patira miniata*	BAT STAR	SEA STAR	ECHINODERM
91 *Unspecified*	CORAL	MISC.	COELENTERATE
92 *Pteraster tesselatus*	ORANGE PEEL STAR	SEA STAR	ECHINODERM
93 *Aulorhynchus flavidus*	TUBESNOUT	FISH	CHORDATE
94 *Pododesmus cepio*	JINGLESHELL OYSTER	BIVALVE	MOLLUSC
95 *Pteraster tesselatus*	SLIME STAR	SEA STAR	ECHINODERM
96 *Hydrolagus colliei*	RATFISH EGG CASE	FISH	CHORDATE
97 *Ophiopholis aculeata*	BRITTLE STAR	SEA STAR	ECHINODERM
98 *Diopatra ornata*	DECORATING TUBEWORM	MISC	ANNELID
99 *Pugettia spp.*	DECORATOR CRAB	CRAB	ARTHROPOD
100 *Unspecified arthropod*	ARTHROPOD	MISC.	ARTHROPOD
101 *Unspecified fish*	FISH	FISH	CHORDATE
102 *Unspecified cnidarian*	CNIDARIA	MISC.	CNIDARIA
103 *Unspecified echinoderm*	ECHINODERM	MISC.	ECHINODERM
104 *Unspecified mollusc*	MOLLUSC	BIVALVE	MOLLUSC
105 *Unspecified worm*	WORM	MISC.	ANNELID
106 *Unspecified marine mammal*	MARINE MAMMAL	MAMMAL	CHORDATE
107 *Unspecified fish eggs*	FISH EGGS	FISH EGGS	CHORDATE
108 *Composmyax subdiaphana*	MILKY PACIFIC VENUS	BIVALVE	MOLLUSC
109 *Glycymeris subobsoleta*	BITTERSWEET ARKSHELL	BIVALVE	MOLLUSC
110 *Humilaria kennerleyi*	KENNERLY'S VENUS	BIVALVE	MOLLUSC
111 *Oregonia gracilis*	DECORATOR CRAB	CRAB	ARTHROPOD
112 *Terebellid sp.*	TEREBELLID TUBE WORM	MISC.	ANNELID
113 *Solen sicarius*	JACK KNIFE CLAM	BIVALVE	MOLLUSC
114 *Semele rubropicta*	ROSE SEMELE	BIVALVE	MOLLUSC
115 *Opisthobranch sp.*	OPISTHOBRANCH	MISC.	MOLLUSC
116 *Sabellid sp.*	SABELLID TUBE WORM	MISC.	ANNELID
117 *Hippasteria spinosa*	SPINY STAR	SEA STAR	ECHINODERM
118 *Pentomera populifera*	MUD CUCUMBER	SEA CUCUMBER	ECHINODERM
119 *Chlamys rubida*	PINK SCALLOP	BIVALVE	MOLLUSC
120 *Chlamys hastata*	SPINY SCALLOP	BIVALVE	MOLLUSC
121 *Leptasterias hexactis*	SIX-RAYED SEA STAR	SEA STAR	ECHINODERM
122 *Patinopecten caurinus*	WEATHERVANE SCALLOP	BIVALVE	MOLLUSC
123 *Scyra acutifrons*	SHARP-NOSED CRAB	CRAB	MOLLUSC
124 *Munida quadrispina*	PINCH BUG	CRAB	MOLLUSC
125 *Sebastes caurinus*	COPPER ROCKFISH	FISH	CHORDATE
126 *Sebastes maliger*	QUILLBACK ROCKFISH	FISH	CHORDATE
127 *Sebastes auriculatus*	BROWN ROCKFISH	FISH	CHORDATE

128	*Platichthys stellatus*	STARRY FLOUNDER	FISH	CHORDATE
129	*Parophrys vetulus*	ENGLISH SOLE	FISH	CHORDATE
130	*Lepidopsetta bilineata*	ROCK SOLE	FISH	CHORDATE
131	*Pleuronichthys coenosus*	C-O SOLE	FISH	CHORDATE
132	*Psettichthys melanostictus*	SAND SOLE	FISH	CHORDATE
133	*Citharichthys sp.*	SANDDAB	FISH	CHORDATE
134	*Cribrinopsis fernaldi*	CRIMSON ANEMONE	ANEMONE	CNIDARIA
135	*Unspecified tunicate*	SESSILE TUNICATES	MISC.	ASCIDIAN
136	*Unspecified bryozoan*	MOSS ANIMAL	MISC.	BRYOZOAN
137	*Unspecified flatworm*	FLATWORM	MISC.	PLATYHELMINTHES
138	*Unspecified peanut worm*	PEANUT WORM	MISC.	SIPUNCULID

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Geoduck Survey Plants List Last updated: 11/10/99

CODE	TAXONOMER	DESCRIPTION	GROUP	COLOR
0	*Elzippo nullus*	NO PLANTS		ENTROPY
1	*Laminaria and similar species*	LAMINARIA	Laminaria	BROWN ALGAE
2	*Nereocystis luetkeana*	BLADDER KELP	Laminaria	BROWN ALGAE
3	*Ulva spp.*	SEA LETTUCE		GREEN ALGAE
4	*Zostera marina*	EEL GRASS		ANGIOSPERM
5		SMALL MIXED ALGAE	red-brown-green	ALGAE
6	*Unspecified*	SMALL RED ALGAE		RED ALGAE
7	*Unspecified*	LARGE RED ALGAE		RED ALGAE
8	*Diatoms*	BROWN SLIME		YELLOW-BROWN ALGAE
9	*Unspecified*	SMALL GREEN ALGAE		GREEN ALGAE
10	*Unspecified*	SMALL BROWN ALGAE		BROWN ALGAE
11	*Pterygophora californica*	FEATHER PALM ALGAE	Laminaria	BROWN ALGAE
12	*Macrocystis integrifolia*	CALIFORNIA KELP	Laminaria	BROWN ALGAE
13	*Unspecified*	LARGE BROWN ALGAE		BROWN ALGAE
14	*Unspecified*	FILAMENTOUS BROWN ALGAE		BROWN ALGAE
15	*Unspecified*	FLUFFY BROWN ALGAE		BROWN ALGAE
16	*Unspecified*	FILAMENTOUS GREEN ALGAE		BROWN ALGAE
17	*Unspecified*	FILAMENTOUS GREEN ALGAE		GREEN ALGAE
18	*Corallina, Bosiella*	ARTICULATED CORALLINE ALGAE	Corrallinaceae	RED ALGAE
19	*Agarum spp.*	AGARUM	Laminaria	BROWN ALGAE
20	*Costaria costada*	COSTARIA	Laminaria	BROWN ALGAE
21	*Alaria nana*	ALARIA	Laminaria	BROWN ALGAE
22	*Pleurophycus gardneri*	PLEUROPHYCUS	Laminaria	BROWN ALGAE
23	*Desmarestia spp*	DESMARESTIA	Desmarestiales	BROWN ALGAE
24	*Gigartina papillata*	GIGARTINA	Gigartinales	RED ALGAE
25	*Porphyra spp.*	PORPHYRA	Bangiales	RED ALGAE
26	*Lithothamnion, Lithophyllum*	CRUSTOSE CORALLINE ALAGE	Corrallinaceae	RED ALGAE
27	*Opuntiella californica*	OPUNTIELLA	Gigartinales	RED ALGAE
28	*Gracilaria verrucosa*	GRACILARIA	Gigartinales	RED ALGAE
29	*Sarcodiotheca gaudichaudi*	SARCODIOTHECA	Gigartinales	RED ALGAE
30	*Polyneura spp.*	POLYNEURA	Ceramiales	RED ALGAE
31	*Enteromorpha intestinalis*	ENTEROMORPHA	Cladophorales	GREEN ALGAE
32	*Phyllospadix scouleri*	PHYLLOSPADIX	Surf Grass	ANGIOSPERM
33	*Egregia menziesi*	EGREGIA	Laminaria	BROWN ALGAE
34	*Fucus distichus edentatus*	FUCUS	Fucales	BROWN ALGAE
35	*Iridea cordata*	IRIDEA	Gigartinales	RED ALGAE
36	*Ceramium spp.*	CERAMIUM	Ceramiales	RED ALGAE

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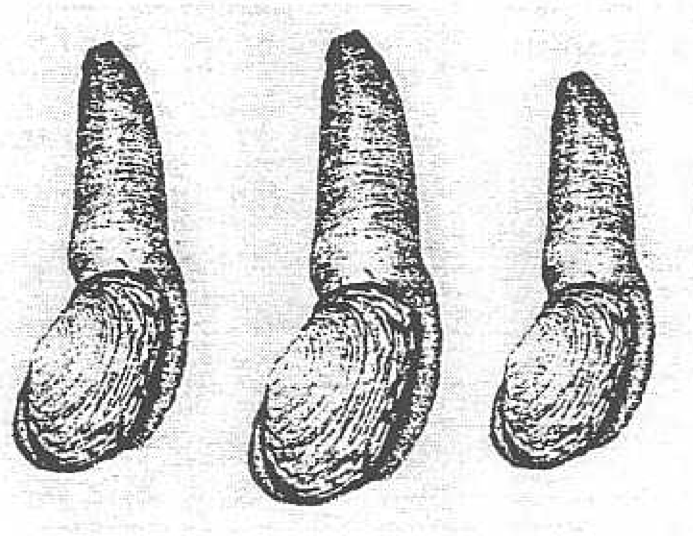
Appendix 4

EBASCO

FINAL REPORT

The Transport and Fate of Suspended Sediment Plumes Associated with Commercial Geoduck Harvesting



Prepared for

State of Washington
Department of Natural Resources

APRIL 1992

EBASCO ENVIRONMENTAL
A Division of Ebasco Services Incorporated

THE TRANSPORT AND FATE OF SUSPENDED SEDIMENT PLUMES ASSOCIATED WITH COMMERCIAL GEODUCK HARVESTING

FINAL REPORT

Prepared for

State of Washington
Department of Natural Resources

Prepared by

Kent S. Short
Raymond Walton
Ebasco Environmental
Bellevue, Washington

April 1992

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SOW.1/4-8-92/02370A

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1.0 INTRODUCTION

1.1 BACKGROUND

Commercial geoduck harvesting by divers using hand-held water jets has been shown to produce turbid plumes of suspended sediment down-current from the harvesting operation (Goodwin, 1978; Breen and Shields, 1983). Concerns raised in appeals to the Shoreline Hearings Board revolve around the issue of the transport and fate of such plumes, and the potential impacts on nearby aquatic communities and beaches due to deposition of material from the plumes.

These issues were addressed to some extent in the Environmental Impact Statement (EIS) for the Puget Sound Commercial Geoduck Fishery (State of Washington, 1985), hereafter referred to as the EIS. However, in light of the recent appeals, the State of Washington desires to explore existing information and to develop additional data relating to the transport and fate of fine particulate materials that may be placed into suspension during geoduck harvesting.

This report presents the results of a study designed to assess, and where possible, expand the existing knowledge base with regard to the physical processes that govern the transport and fate of such material. Biological impacts associated with geoduck harvesting are being addressed in a separate study.

1.2 OBJECTIVES

The general objectives of this study were threefold:

1) Provide an independent technical review of the EIS with respect to physical processes, in light of the current state of knowledge regarding such processes.

2) Collect additional data to extend the existing knowledge base in subject areas where information gaps are found to exist.

3) Augment the observational data base using analytical techniques (theoretical and empirical modeling) to quantify the transport and fate of suspended sediments under a variety of conditions.

1.3 APPROACH

The approach to achieving the first objective was to critically examine the results and conclusions presented in the EIS with respect to basic physical processes. This involved examining the reference material cited in the EIS, as well as searching for any other pertinent literature. Calculations resulting in numerical results stated in the EIS were checked. Weaknesses or omissions in the EIS, as well as gaps in the existing knowledge base related to potential physical impacts of geoduck harvesting, were identified. The results of this review are presented in Section 3.0.

It was clear from the outset that very limited observational data had previously been collected regarding the transport and fate of material suspended by the geoduck harvesting operation. Therefore, it was felt that achieving the second objective of the study would require a limited-scale field measurement program designed to track and quantify the suspended sediment in the plume associated with an actual harvesting operation. A water sampling program was designed and carried out using seven divers at specified fixed sampling stations down-current from an actual geoduck harvest diver working on the Nisqually Reach tract. Results from this experiment were used to extend the existing data base on plume behavior and suspended sediment concentration in the plume, as well as to calibrate the particle tracking model described below. The field data collection program is discussed in Section 4.0.

The third study objective, being the augmentation of observational data with analytical calculations of suspended sediment behavior under a variety of conditions, consisted of three principal elements. In the first element, the transport and fate of the initial plume raised by the harvesting operation was numerically modeled using a particle tracking model. This model jointly considered the physical transport processes of advection (direct transport by currents), settling (particle fall rates as a function of size and density), and dispersion (horizontal spreading and dilution of the plume). The model also allowed consideration of a moving source (the geoduck harvest diver), and incorporated flexibility in the input parameters to facilitate examination of a wide variety of possible application scenarios. The particle tracking model and it's application are described in Section 5.0.

The second element of the analytical approach involved semi-empirical calculations of bottom sediment resuspension under current and wave forces. These calculations were used to evaluate the likelihood of resuspension and further transport of fine particulate material deposited on the bottom after settling out of the initial plume. The results of these calculations are presented in Section 6.0.

The third and final element of the analytical portion of this study involved calculations of beach deposition and erosion parameters in order to assess the likelihood of fine material being deposited in and subsequently eroded from intertidal beach zones near the geoduck harvesting tracts. Section 7.0 describes this analytical approach and results.

We have adopted a conservative scientific approach in all elements of this study. That is, where uncertainty exists, we have made assumptions and chosen techniques that are most likely to err on the side of greater, rather than lesser, impacts on the environment than actually exist. This approach provides a margin of safety in such assessments.

2.0 REVIEW OF EXISTING INFORMATION

The limited amount of time allotted for this study necessitated a focused approach to the examination of existing information. Fortunately, a number of key references were provided or suggested by L. Goodwin (Washington Department of Fisheries) and R. Sternberg (University of Washington) on the subjects of the physical effects of geoduck harvesting and sediment transport, respectively.

2.1 PHYSICAL EFFECTS OF GEODUCK HARVESTING

Very little published information is available on the transport and fate of sediment that is disturbed and/or placed into suspension during the harvesting of geoducks using the hand-held water jet technique. In fact, the only references that could be located presenting any quantitative estimates of the effect of geoduck harvesting on substrate composition were those conducted by Goodwin (1978) and Breen and Shields (1983), both of which were referenced and discussed in the EIS. Goodwin noted changes in sediment grain size distribution between sediments in harvest holes immediately after harvest and in undisturbed nearby substrate that suggested a small but statistically significant loss of fine material (less than 63 micron grain size) from the holes. Breen and Shields concluded that there was no impact on the substrate composition due to harvesting, although their comparisons did not include sediment grain size distribution in holes immediately after harvest.

Studies of suspended sediment and bottom substrate impacts due to commercial hydraulic clam harvesting have been conducted at several locations in Puget Sound (Port Susan, Kilisut Harbor, and Agate Passage) (Schwartz and Terich, 1977; Tarr, 1977), and in the Harraseeket River, Maine (Kyte et al., 1975). The results of these studies indicate that bottom sediment composition, as determined by core samples, was not significantly affected by the clam harvesting operations.

Total suspended solids (TSS) and turbidity in the vicinity of hydraulic clam harvesting operations were found to increase near the bottom at distances of from 50 to 150 yards down-current from the harvest vessel in Puget Sound (Tarr, 1977). However, such effects were found to dissipate quickly, and the incremental elevation in TSS concentrations were small in comparison to the natural variability in suspended material from fluvial sources.

It should be noted that the hydraulic clam harvesting operation is considerably more invasive than the geoduck harvesting technique employing divers with water jets, in that much more sediment is disturbed over a greater area per unit time. Even if the aforementioned studies had determined that significant bottom sediment and water quality impacts existed due to hydraulic clam harvesting, the results would not be directly applicable to geoduck harvesting, due to the different spatial and temporal scales involved.

2.2 SEDIMENT PLUME TRANSPORT

Sediment plumes associated with a number of natural and anthropogenic sources have been studied. Such studies span a range of scales, from major river effluent plumes (tens to hundreds of km) (Barnes et al., 1972) to plumes associated with dredge spoil dumping (tens to hundreds of m) (Nittrouer and Sternberg, 1975). The theoretical basis for sediment transport mechanisms is treated in Graf (1971). Engineering aspects of sediment transport in the nearshore environment are discussed in (USACOE, 1984).

Numerical modeling of plumes has been performed for a variety of applications, including coastal sedimentation and erosion studies, environmental impact assessment for coastal engineering projects, effluent discharge permits and hazardous waste remediation studies, and oil spill trajectory analyses. Unfortunately, the sediment plume induced by geoduck harvesting presents several unique modeling problems, which precluded the use of any "off-the-shelf" models developed for other types of applications. First, the time and spatial scales of the plume are quite small. Second, the source point of the plume (the geoduck diver) is moving in space, unsteady in time (i.e., produces "pulses"), and exhibits a considerable degree of randomness. Third, the plume is ejected into a fluid that has a non-steady-state velocity (i.e., changes in direction and speed with the tide). Finally, from previous studies there is only limited data on the actual source strength (how much sediment is suspended per each hole dug) and no data at all on down-current suspended sediment concentrations for use in model validation. To our knowledge, no previous studies have been performed that address these unique concerns.

2.3 SEDIMENT DEPOSITION AND EROSION

A profusion of reference material exists on the subject of sediment deposition and erosion under the influence of waves and currents in a wide variety of environment types. Much of this material is summarized in review volumes edited by Seymour (1989), Stanley and Swift (1976), and Swift et al. (1972).

In reviewing appropriate techniques for calculating the potential for resuspension of fine sediments deposited from geoduck plumes, as well as possible deposition and erosion of fine material in the intertidal zone, we concentrated on semi-empirical studies (i.e., those using actual field or laboratory measurements, but having an underlying theoretical basis). Examples of such references include: Miller et al. (1977); Komar and Miller (1973, 1975); Grant and Madsen (1979); Southard et al. (1971); and Lavelle et al. (1984). Techniques extracted from these studies formed the basis of the calculations presented in Sections 6.0 and 7.0 of this report. Given the limitations on available data in this study, such semi-empirical techniques were felt to provide the most straightforward and least error-prone means of estimating depositional/erosional tendencies.

3.0 TECHNICAL REVIEW OF THE EIS

Our review was limited to an evaluation of the EIS with regard to the physical aspects of the natural environment. Consequently, we focused on Subsections 3.1 (Earth), 3.2 (Air), and 3.3 (Water), within Section 3.0 (ASSESSMENT OF IMPACTS TO THE NATURAL ENVIRONMENT). Each of these subsections are discussed below. First, however, we offer several general comments on the content of the EIS.

The authors of the EIS were hampered by the lack of observational or model output data upon which to base their conclusions. Given this limitation, the subject sections provide a reasonable attempt to quantify some of the more obvious effects that might be associated with sediment suspension during harvesting activities. These include rough calculations of the thickness of redeposited plume material and changes in the suspended sediment concentration in the overlying water. Our overall finding is that the general conclusions in the EIS regarding impacts to the physical environment due to commercial geoduck harvesting are valid. We did, however, identify some deficiencies in the EIS discussions in the form of subject matter omissions and numerical inconsistencies.

First, there was no quantitative discussion of the transport and fate of the initial plume produced by the harvesting activity. As the EIS states, no studies had been conducted to actually follow the displaced material. This emphasizes the speculative nature of many of the numerical results presented.

There was also no attempt to quantify the likelihood of resuspension and further transport by waves and currents of unconsolidated sediment redeposited on the bottom after settling out of the plume. Some readily available references or relatively simple calculations could have provided a rough determination of the possible importance of such processes. Likewise, there was no discussion of the possible deposition and likelihood of retention of fine suspended sediments in the intertidal zone of beaches surrounding the harvest tract.

Finally, there was no discussion of bottom sediment placed into suspension by the activities of the geoduck divers, beyond that disturbed during the digging of the actual hole. Through conversations with Washington Department of Fisheries (WDF) and Department of Natural Resources (DNR) personnel, and first-hand observation of a harvest diver in action, it became apparent to us that a significant amount of surficial sediment is disturbed by the diver's activities, including moving (or "jetting" with the water jet) along the bottom and dragging hoses or bags. Although estimation of the quantity of sediment disturbed in this manner is virtually impossible, visual appearances suggest that it may amount to a significant additional source of suspended material beyond that which is displaced in the actual digging of the holes. Furthermore, the diver's activities not only raise more suspended sediment, but his movement around or through the initial plume also serves to disperse the suspended material over greater horizontal and vertical scales than would be expected due to natural advection and dispersion processes in the current. Consequently, impact estimates based only on the loss of material from the actual holes are likely to be underestimates.

3.1 EARTH

Section 3.1 of the EIS (p. 107-110) discusses potential impacts due to geoduck harvesting on the bottom sediment distribution and composition. The numerical estimates given in this section are based entirely on data presented by Goodwin (1978), which is appropriate given that Goodwin's study was the only known source of data (prior to the present study) specifically dealing with bottom sediment changes immediately after geoduck harvesting. We confirmed that the calculated results presented in this section were correct in light of Goodwin's data. One of the findings states that if all the fine material released from the geoduck holes in a given tract during a year's harvest were redeposited on the tract itself (a conservative assumption), it would constitute a layer only 0.02 cm thick. That such a small layer is inconsequential could have been underscored if it had been compared to estimates of annual average natural sedimentation in various areas of Puget Sound. For example, the natural sedimentation rate in the Nisqually delta area is approximately 1.7 cm/yr (Brundage, 1960), two orders of magnitude greater than the conservative EIS estimate.

The main weaknesses of this section of the EIS include: lack of discussion of sediment suspended by the diver's activities; lack of estimates of potential resuspension of unconsolidated bottom sediment by wave and current forces; and lack of discussion of potential intertidal zone deposition and retention of fine sediments. The point should also have been made that Goodwin's results, upon which the numerical estimates in this section were based, came from an experimental (not commercial) plot in Hood Canal, and may not be directly transferable to other Puget Sound sites due to differences in substrate composition.

Although the above topics should have been addressed, we believe that their consideration would not have changed the overall conclusions in the EIS regarding the significance of substrate impacts.

3.2 AIR

After consideration of the small number and spatial separation of the boats involved in harvesting, we concur with the conclusion that there will be no significant impact on air quality.

3.3 WATER

Some omissions and inconsistencies were noted in reviewing the numerical results presented in this section of the EIS.

In paragraph 1, page 112 ("No studies have..."), physical dimensions of the suspended sediment plume down-current from the harvesters are provided. This is a critical issue, yet no reference is provided on the source of this information.

Paragraph 2, page 112 ("Goodwin (1978c) observed...") presents several numerical results in inconsistent units (liters, cubic meters, gallons). There also appears to be a numerical error in this paragraph, where it is stated that "the amount of fines released from an average harvest hole is equivalent to about 0.91 liters...". This number is inconsistent with both the calculations presented on page 109 and the estimate of 0.81 cubic meters of fines released in 10,000 holes presented later in this paragraph. There appears to be an approximate factor of ten error in the 0.91 liter value. However, this number does not appear to have been used in subsequent calculations described later in this paragraph. The estimated change in suspended solid concentration of 0.2 ppm by volume is correct.

4.0 FIELD DATA COLLECTION

4.1 OBJECTIVES

Given the very limited amount of existing data on the transport and fate of sediment suspended during geoduck harvesting, the objectives of the field data collection portion of this study were:

(1) To provide additional observational data on the behavior of the suspended sediment plume associated with commercial geoduck harvesting; and

(2) To provide actual in-situ measurements that could be used to calibrate the numerical model used in this study.

4.2 METHODS

The field data collection activity, which occurred on February 18, 1992, was coordinated by Pentec Environmental. WDF, DNR and Ebasco Environmental staff participated in the experimental design and assisted with field logistics. Prior to finalizing the sampling design, Ebasco Environmental and Pentec staff participated in an orientation dive in the company of DNR divers to observe an actual commercial harvesting operation and the resulting plume.

The importance of obtaining realistic measurements dictated that the field experiment occur during an actual commercial harvesting operation in an existing commercial tract. To this end, cooperation with commercial harvesting operators was sought and obtained. The experiment occurred in the western portion of the Nisqually Reach Tract near Sandy Point.

Two types of sediment data were required. These included total suspended solid (TSS) concentrations in the affected water column down-current from the harvester, and particle size distributionss from bottom sediment cores collected in the immediate vicinity of the experiment.

4.2.1 TSS

A sampling plan was devised to allow a series of synoptic "snapshots" of TSS concentration at seven locations ranging between zero and 100 m down-current from the geoduck harvesting operation (Figure 4-1). A sampling grid was laid out on the bottom using measured lines, and sampling locations were marked by floats attached to small anchors. The long axis of the sampling grid was chosen to align with the prevailing flood tidal current at the experimental site (as determined by diver observation of near-bottom drift direction).

A 30 m by 30 m square in which the geoduck diver was to work was also marked by lines on the bottom. Timing was coordinated between the geoduck diver and seven sampling divers stationed near the bottom at the designated points on the sampling grid. The geoduck diver actively harvested geoducks within the square from time=0 to time=20 minutes, while the sampling divers collected 1-liter water bottle samples every five minutes, starting at time=0 and ending at time=30 minutes (ten minutes after the geoduck diver stopped harvesting). Before and after his harvesting activity, the geoduck diver remained stationary, and water pressure to his hand-held jet was turned off to avoid unintentional sediment disturbance. Upon conclusion of the experiment, the geoducks harvested by the diver were counted. During the 20 minute harvesting period, the diver harvested 24 geoducks, yielding an average time interval of 50 seconds between holes.

All of the sampling divers were instructed to collect samples at approximately 1 m off the bottom. The divers stationed at the two farthest down-current stations (60 m and 100 m) collected double samples to allow more accurate determination of low concentration values.

The water bottle samples collected during the experiment were submitted within 24 hours to an analytical laboratory for analysis of TSS and turbidity.

4.2.2 Bottom Sediment Composition

In addition to the water samples, three bottom sediment cores were collected on the day of the experiment by a diver using a hand-held coring device. These included two control cores taken in undisturbed sediment adjacent to the experiment grid, and one core taken in a harvested geoduck hole shortly after harvest.

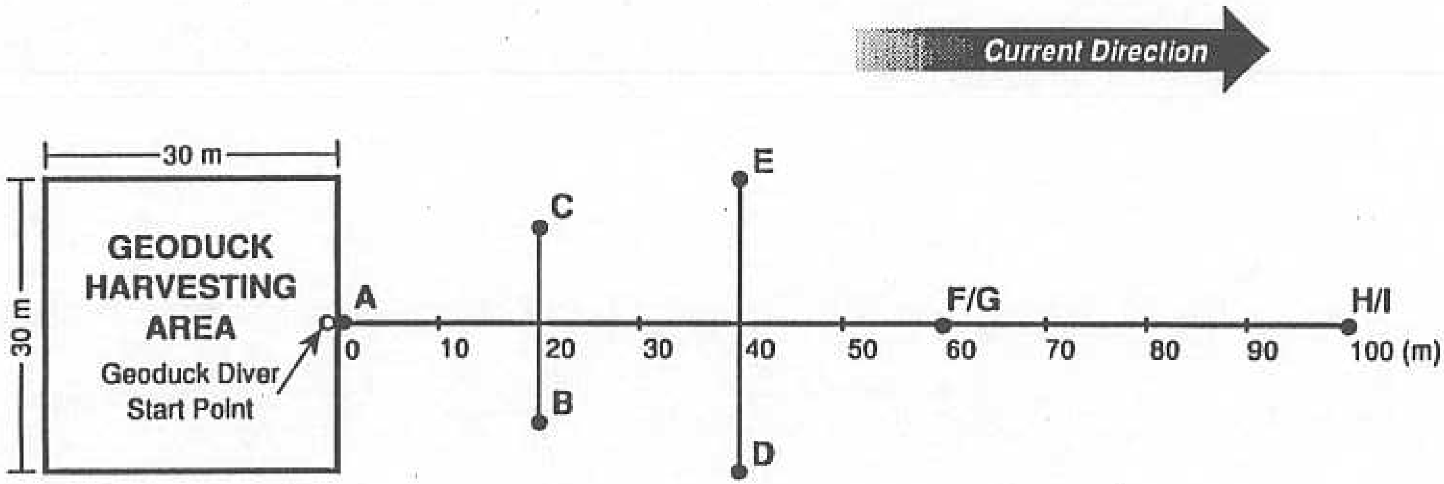


Figure 4-1. Field sampling station locations.

The three core samples were refrigerated and submitted within 24 hours to an analytical laboratory for grain size analysis.

4.2.3 Current Speed

The timing of the experiment was set to coincide with the maximum predicted flood current of the day. Although the predicted maximum flood current was approximately 0.5 m/s (1 kt) for the central Nisqually Reach (NOAA Tidal Current Tables), we anticipated a lower current in the experiment area further west.

During the course of the experiment, current measurements were taken from a support boat immediately adjacent to the experiment grid. The current meter used was a Swoffer Model 2100, with an on-deck digital readout in m/s. The averaging period was set at 30 seconds. This instrument has a nominal speed measurement threshold of 0.03 m/s.

Seven current measurements were manually recorded during the 30 minute experiment. The measurement height above the bottom alternated between 1 m and 3 m, in order to encompass the likely vertical extent of the plume.

4.3 RESULTS

4.3.1 TSS

The TSS results are summarized in Table 4-1. In general, TSS during the experiment was very low. The background value, as determined from samples taken at time t=0 and at stations too far down-current to be affected by harvesting-related plumes, averaged approximately 4 mg/l, which is the minimum reporting limit used by the laboratory in analysis of TSS. In several cases, the value measured was below the reporting limit. For these samples, we assumed a TSS value equal to the average background. Table 4-1 also presents the calculated deviation from background, determined by subtraction. This deviation from background was used in comparing the observed results to the modeled results (see Section 5.3).

The double water samples collected by the divers farthest down-current (60 and 100 m) were combined in the analysis. For unknown reasons, TSS values from one station (H/T) appeared to be contaminated for several sampling times, as indicated by inconsistency

Table 4-1. Total suspended solid (TSS) concentrations measured at plume sampling stations at the Nisqually Reach experiment site, February 18, 1992.

Time (min)	TSS (mg/l)							TSS Deviation From Background (mg/l)[1]						
	A[2]	B	C	D	E	F/G	H/I	A	B	C	D	E	F/G	H/I
0	13	5	4	<4[3]	<4	5	10[4]	9	1	0	0	0	1	6[4]
5	7	5	<4	<4	5	<4	9[4]	3	1	0	0	1	0	5[4]
10	21	4	4	4	5	5	6[4]	17	0	0	0	1	1	2[4]
15	4	5	<4	6	4	5	<4	0	1	0	2	0	1	0
20	10	9	10	4	5	<4	<4	6	5	6	0	1	0	0
25	14	<4	4	4	5	5	12[4]	10	0	0	0	1	1	8[4]
30	13	<4	4	4	8	11	4	9	0	0	0	4	7	0

1/ Background was determined to be 4 mg/l.
2/ See Figure 4-1 for station locations.
3/ Values given as "<4" indicate a concentration below laboratory reporting limit. Deviation from background in such cases was set at zero.
4/ Sample suspected of possible contamination.

with the other samples and the probable timing of plume movement given the measured current.

As expected, the highest TSS values were reported at station A, closest to the harvest diver. Increases in TSS were also seen at stations B and C at t=20 minutes, and at stations E and F/G at the end of the experiment (t=30 minutes). Since uncertainty exists regarding the data validity at station H/I, we can only say with some confidence that the plume generated by the geoduck diver reached station F/G, 60 m down-current, by the end of the experiment. This is roughly consistent with the measured current speed during the experiment, which averaged 0.034 m/s (see Section 4.3.3 below). At this average speed, the plume front would have been advected 61.2 m from the source during 30 minutes.

4.3.2 Bottom Sediment Composition

The grain size analysis for the three bottom sediment cores is shown in Table 4-2. Grain size percentages were determined for three size categories: greater than 500 microns (coarse sand), 62.5 to 500 microns (fine and medium sand), and less than 62.5 microns (silt and clay). The last category is most relevant to this study, since the fine sediments ("fines") are those which remain suspended longer, and are available for transport and redeposition away from their source substrate.

The three cores taken at the experiment site are very similar in grain size composition. The core taken in the geoduck harvest hole soon after digging shows slight reductions in both coarse and fine fractions, in apparent agreement with the findings of Goodwin (1978). However, with only three samples, the small differences in the results shown here cannot be considered significant. Goodwin (personal communication) has indicated that typical values of fine sediment percentage for geoduck beds range from about 4 to 10 percent. The average value of 8 percent determined from the three cores collected in this experiment are therefore within the normal range. The 8 percent value was used in the numerical modeling portion of this study.

4.3.3 Current Speed

Measured current speeds during the experiment were weak and variable, in many cases at or below the nominal measurement threshold of the current meter (Section 4.2.3). The

Table 4-2. Sediment core grain size composition (percent by weight in each size class) for three bottom cores taken at the Nisqually Reach experiment site, February 18, 1992.

Sample	Grain Size (microns)		
	>500	62.5-500	<62.5
Control A[1/]	5	86	9
Control B[1/]	5	87	8
Hole[2/]	4	88	7

1/ Control samples were taken in undisturbed substrate immediately adjacent to the experiment site.

2/ Hole sample was taken in a recently harvested geoduck hole within the experiment site.

absolute accuracy of the measurements is therefore uncertain. However, the average speed of the measured current (Table 4-3) was found to be consistent with the apparent movement of the suspended sediment plume, as indicated by the TSS samples.

Table 4-3. Current speeds measured at the Nisqually Reach experiment site, February 18, 1992.

Time[1/] (min)	Current Speed (m/s)	Height Above Bottom (m)
-2	0.04	1
0	0.06	1
6	0.01	3
10	0.00	1
15	0.02	3
16	0.09	3
20	0.02	1
	Average 0.034	

1/ Time referenced to start of TSS sampling.

5.0 TRANSPORT AND FATE OF INITIAL PLUME

5.1 MODEL DEVELOPMENT

5.1.1 Approach

There are three general types of models that might be used to simulate the transport and fate of particulate matter placed into suspension during geoduck harvesting:

1. Particle tracking models, in which the transport and settling of individual particles are simulated.

2. Analytic models that simplify the governing transport and fate equations to a point where a simple expression is developed. Generally, simplifying assumptions include steady-state currents.

3. Numerical models that directly solve the governing transport and fate equations.

In general, we preferred the first approach due to its efficiency and relative conceptual simplicity. In our view, analytic models are too limiting, and numerical models, while providing a complete description, are not as straightforward as particle tracking models for this application.

The modeling tasks in this study faced several unique complicating factors which precluded the use of existing models developed for other sediment transport applications. Principal among these complications were the facts that the suspended sediment source (the geoduck harvester) is moving spatially, unsteady in time (i.e., generates pulses), and injects material into a fluid having a periodic current variation (tidal current). Furthermore, considerable uncertainty existed regarding the source strength (amount of material suspended per unit time).

5.1.2 Processes Simulated

The particle tracking model, GEODUCK, simulates the following processes:

1. Source distribution of particles
2. Moving source
3. Particle advection
4. Three-dimensional dispersion
5. Particle settling

Source Distribution of Particles

We assumed that each hole created during geoduck harvesting produces a known quantity of particulate material. For the purposes of defining this quantity, we have used average hole size estimates given by Goodwin (1978). Given a possible range of sediment saturation, the resulting variation in density implies that approximately 20 kg of material is displaced in each hole.

It is also necessary to know the distribution of particle grain sizes in the displaced material. For the Nisqually Reach tract, the grain size distribution was obtained from sediment cores taken by Pentec Environmental as part of the field data collection program (see Section 4.0). This grain size distribution is within typical ranges found by Goodwin (personal communication) for geoduck beds. For adequate model simulations in other areas, site-specific bottom sediment composition data would be required.

Using the number of sediment size classes provided in the bottom core data, GEODUCK subdivides each size class into an equal number of intervals based on the user-specified number of particles for that class. The weight of each particle is determined by the diameter of the particle, and scaled by the percentage range of the size class and the number of particles released. Finally, the individual particle weights are scaled to the total weight of particulates released from a hole.

Each hole created is assumed to release material into a cylindrical volume of user-specified dimensions. All of the particles simulated for each hole are released randomly into this initial cylindrical volume. Based upon first-hand observations, and discussion with WDF and DNR personnel, we set the cylinder's height at 1.5 m and diameter at 2.0 m for all model runs. This initial dilution volume was intentionally chosen to be somewhat larger than the initial plume raised by digging the geoduck, in the hopes of partially accounting for the dispersive activities of the diver himself.

Moving Source

If the down-current area of concern is relatively far from the harvesting site, the movement of the source (the diver) may not be very important in determining suspended sediment concentrations. However, in the most conservative approach, the source movement must be taken into account in assessing near-field maximum suspended and settled out concentrations.

In GEODUCK, a moving source is permitted along a user-specified track. The track of a diver is defined by as many x-y positions and times as may be applicable. The user specifies the time increment between geoduck holes, and the model then interpolates hole positions as a function of time along the specified track. In our model simulations, we used an idealized "zig-zag" path for the diver moving generally up-current, and assumed a time increment of 50 seconds between each hole, in line with field observations.

Particle Advection

Advection represents the direct transport of particles by the current. Ambient currents are assumed to be of a sinusoidally varying form, with an amplitude equal to the maximum tidal current at any location, and a period equal to the tidal period (12.42 hours). The coordinate system used by the GEODUCK model is aligned with the major current direction, so that the particle displacement due to advection between any two time steps is simply given by the current speed multiplied by the time step.

Particle Dispersion

Dispersion is the three-dimensional spreading process in a fluid due to random turbulence within the velocity field. This model allows the user to specify the lateral, longitudinal, and vertical dispersion coefficients, based on previous empirical studies or model calibration runs. We chose horizontal dispersion coefficients that were a factor of ten (order of magnitude) larger than the vertical dispersion coefficient, based on visual field observations that indicated only small vertical dispersion of the suspended sediment plume.

The dispersion calculation used in GEODUCK introduces randomness into the motion of each particle. Consequently, it is not possible to exactly duplicate the results of a given model run. However, when a large number of particles are simulated, the statistics of the three-dimensional mass distribution are preserved.

Particle Settling

The particle settling algorithm in GEODUCK follows the approach described in USACOE (1984). In this method, a buoyancy parameter is defined, that is a function of the specific gravities of the fluid and the particles, the kinematic viscosity of the fluid, and the particle diameter. The functional relationship between these variables produces settling velocities that are in close agreement with classical semi-empirical formulations (Sverdrup et al., 1942).

Our approach did not take into account possible flocculation (aggregation) of very fine particles. Although this phenomenon is known to occur for fine silt- and clay-sized particles (less than about 10 microns in diameter), it is very difficult to quantify (R. Sternberg, personal communication). Disregarding this process, however, may be seen as a conservative assumption, since any flocculation occurring will tend to increase the size and weight of the particles, and cause more rapid settling of fine suspended material.

5.1.3 Model Input and Output

The GEODUCK model was designed to allow the user a great deal of flexibility in specifying input parameters so that the model can be used in a wide variety of different situations. Model input variables that may be specified by the user include:

- Mass of sediment released per hole
- Sediment grain size distribution
- Specific gravity of the sediment
- Number of particles to be simulated in each size class
- Dimensions of initial dilution volume
- Time interval between geoduck holes

- Diver track
- Maximum current speed
- Water depth
- Dispersion coefficients
- Harvesting duration and model simulation duration
- Dimensions of the simulation area

The model produces two types of two-dimensional mapped display output:

- Spatial distribution of TSS concentration in g/m^3 (equivalent to mg/l)
- Spatial distribution of settled mass concentration in g/m^2

Note that the TSS concentrations computed are in reality deviations from background, since the model is simulating only effects from the geoduck harvesting source. To obtain the true TSS, it would be necessary to add in the background concentration, if known.

5.2 MODEL TESTING

The program GEODUCK was subjected to a number of basic performance tests to ensure that it was operating properly. The simulations were designed to test each component of the program.

The first test was to ensure that the program was correctly advecting particles. The model was modified to use a constant velocity, and the particle positions printed out after a specified time interval. Results were found to agree with constant advection calculations.

The second test was to ensure that particle settling was correctly programmed. For this test, the particle diameters, positions, and computed settling velocities were printed out. Examination of the results confirmed that the model was operating properly.

The third test was of model dispersion in one dimension (the longitudinal direction of flow). For an instantaneous disturbance of mass, the concentration of particulate mass at the center of the plume was compared to theoretical results for two time periods. The results were in close agreement.

The fourth and final basic performance test was to examine the source terms. A track was defined and the coordinates of the individual holes printed out to ensure that the model was correctly simulating their locations. In addition, at the end of each simulation, a mass balance table was printed out that accounted for the mass settled, the mass in suspension, and the mass that had left the specified grid area. In all cases, the holes were correctly located, and the total amount of particulate mass was conserved.

In addition to the model performance tests, an additional series of test simulations were run to test the sensitivity of the model to changes in various input parameters. Sensitivity tests were run to examine the effects of changing the source strength, dispersion parameters, particle grain size distribution, diver track, and current speed. By means of these tests, we were able to arrive at tentative values of input parameters that appeared to produce the most realistic simulation of visually observed plume behavior.

5.3 MODEL CALIBRATION

The tests described in the previous section brought the model to a point where we were confident it was working properly. The next step involved using actual field data to calibrate the model. In the calibration process, model parameters are adjusted to achieve maximum agreement between observed and modeled results. This then allows further modeling to examine scenarios for which no observed data exist.

The field data used for model calibration consisted of TSS values determined for the nine sets of water samples collected by divers down-current from a geoduck harvester during the field study described in Section 4.0. The model calibration results showing best agreement with observations produced an average error of (-) 0.4 mg/l, a root-mean-square (RMS) error of 3.0 mg/l, and a correlation coefficient of 0.7 (significant at the 99% confidence level for n=39). Some sample data collected by the farthest downcurrent diver (H/T) appeared to be contaminated, and were excluded from this analysis (see Section 4.3).

Based upon these results, we concluded that the source terms, dispersion coefficients, settling rates, and other model variables were set at reasonable values, and the running of further simulation scenarios could proceed.

5.4 MODEL APPLICATION

5.4.1 Description of Modeled Scenarios

For the purposes of this study, all of the input variables were set at reasonable values based on the calibration calculations and held constant, with the exception of the current speed. Four separate model simulations were run, using the following current speeds: 0.05 m/s, 0.25 m/s, 0.5 m/s, and 1.0 m/s. These current speeds were chosen to cover the range of current speeds that would be typically encountered on commercial geoduck harvest tracts.

The model grid was set up using the same 30 m x 30 m harvesting area defined in the field experiment, and an idealized zig-zag path was specified for the geoduck diver. As in the case of the field experiment, for each model run the diver was assumed to harvest for a total of 20 minutes, digging a hole every 50 seconds (averaging 1.2 holes per minute).

The down-current length of the model grid was set at 200 m. This distance was chosen because it corresponds approximately to the 200 yd offshore limit to which the commercial harvesters are restricted. Under hypothetical conditions in which the current would be oriented directly onshore, this configuration would represent the worst case for transport of suspended sediment into the intertidal zone. Of course, a directly onshore current is a highly unrealistic scenario, since nearshore currents tend to be predominantly alongshore. However, the onshore transport assumption does provide the most conservative estimate of impacts in the intertidal zone.

The total size of the model domain used in these runs was set slightly larger than the harvesting area and down-current grid, to ensure that horizontal dispersion did not carry material out of the model domain in the up-current or lateral directions. The total dimensions of the model domain were 60 m x 240 m, for a total area of 14,400 m^2.

5.4.2 Model Results

Figures 5-1 through 5-4 show the model results for TSS for the four current speeds specified. Each of these figures presents concentration values at the end of the 20 minute harvesting period, which represents the time in each model run at which the maximum amount of sediment is suspended in the water. The concentrations (in mg/l) have been contoured at logarithmic intervals (powers of ten).

These plots show that the highest concentrations (greater than 100 mg/l) are confined to a small area surrounding the last hole dug by the diver. Also, the results aptly illustrate how the plume loses its integrity as the current speed increases. At the higher current speeds (0.50 m/s and 1.0 m/s), the suspended sediment down-current from the source is segregated into self-contained clouds of suspended sediment, each representing the material released during the digging of one hole.

The concentration of material settled on the bottom for each of the four current speed cases is depicted in Figures 5-5 through 5-8. For these model runs, the simulation time was extended long enough so that no material remained suspended in the water within the model domain; that is, all of the sediment in the plume either settled out or was advected out of the model domain (past the 200 m line). For these simulations, then, the contours shown (in logarithmic intervals) represent the maximum bottom deposition. Units of settled concentration are g/m^2.

These plots show that at low current speeds, the pattern of deposition closely followed the diver's track, and the highest settled concentrations were found almost entirely inside the harvesting area, within a few meters of the harvested holes. As the current speed increased, the pattern of deposition was displaced down-current and showed less resemblance to the diver's track. For the 0.05 m/s case, virtually all deposition occurred within the first 100 m down-current from the harvesting area. For the three higher current speed cases, small quantities of material were deposited all the way to the 200 m endpoint.

Although the model does not compute a settled sediment thickness, such a conversion is relatively simple if one assumes a representative sediment bulk density. The sediment bulk density takes into account the density of the solid grains themselves (assumed to be 2.65 g/cm^3), as well as the porosity of the settled sediment and the density of the

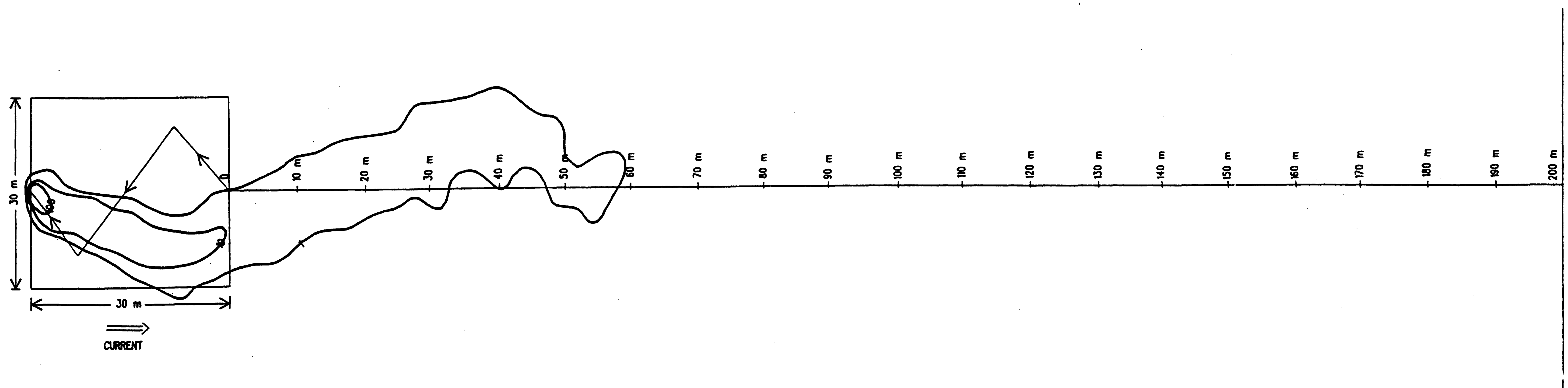


Figure 5-1. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 0.05 m/s.

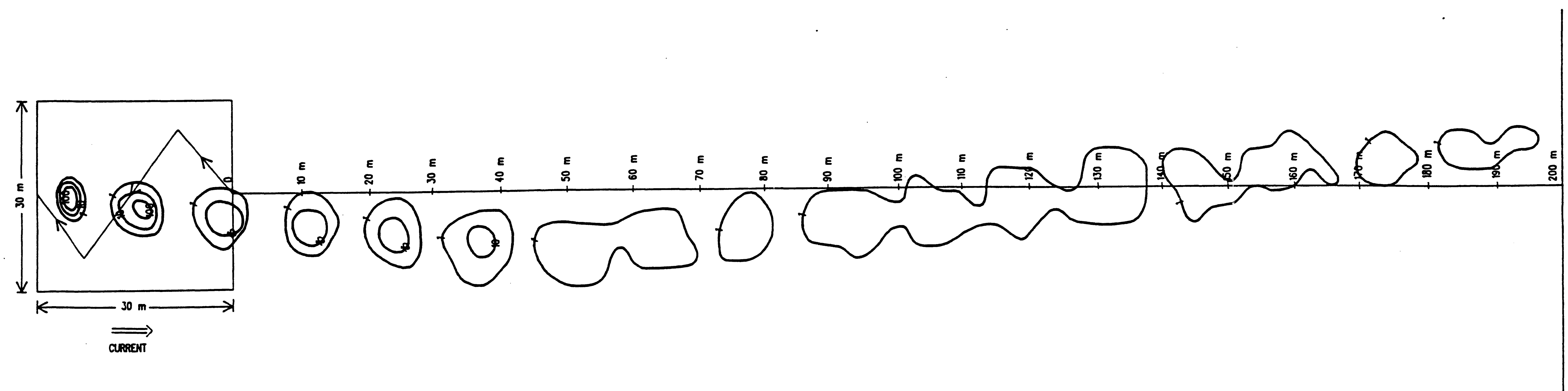


Figure 5-2. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 0.25 m/s.

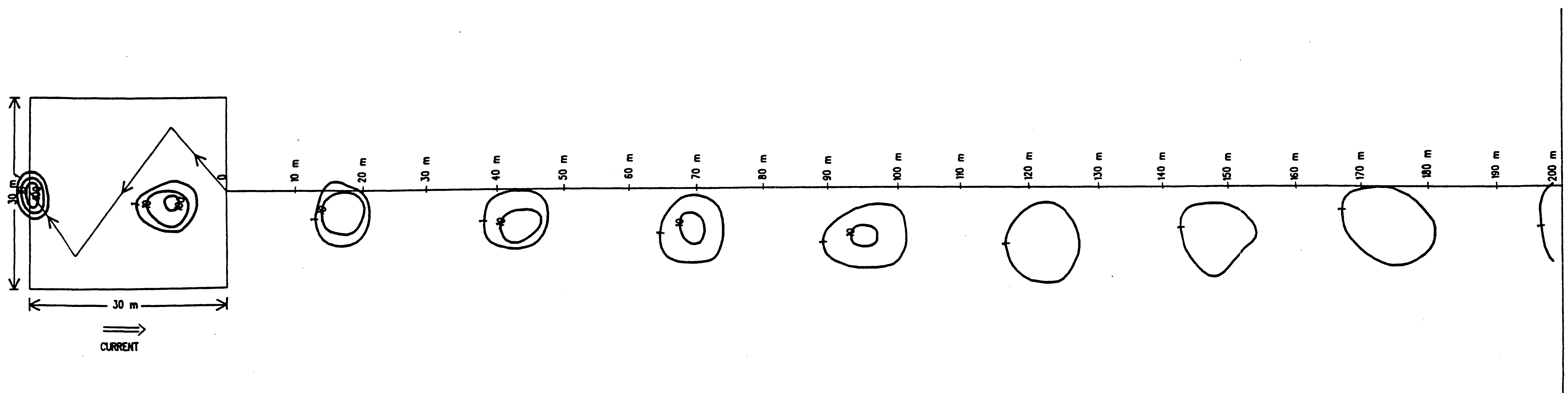


Figure 5-3. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 0.5 m/s.

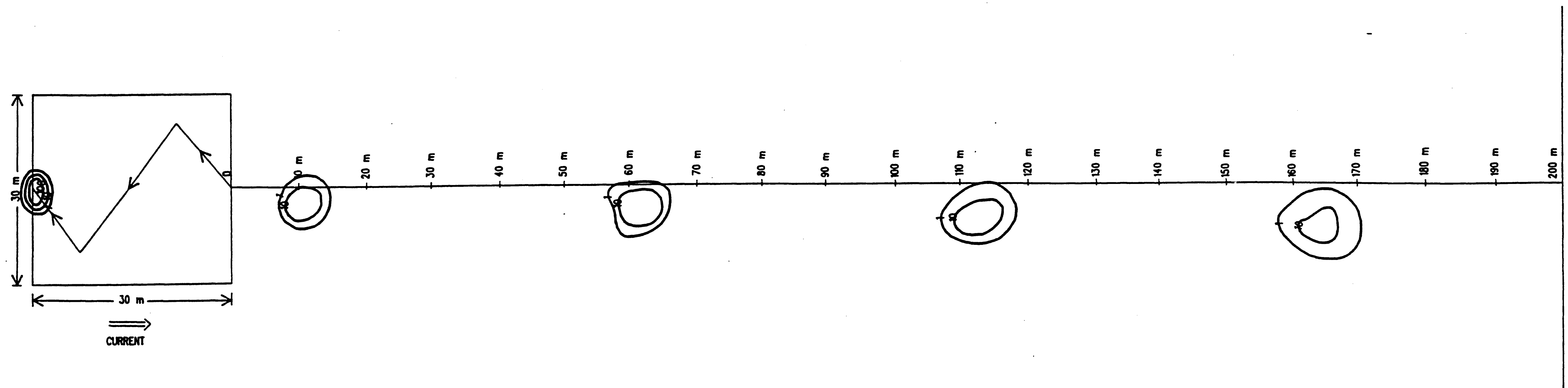


Figure 5-4. TSS contours (mg/l).
Time = 20 minutes.
Current speed = 1.0 m/s.

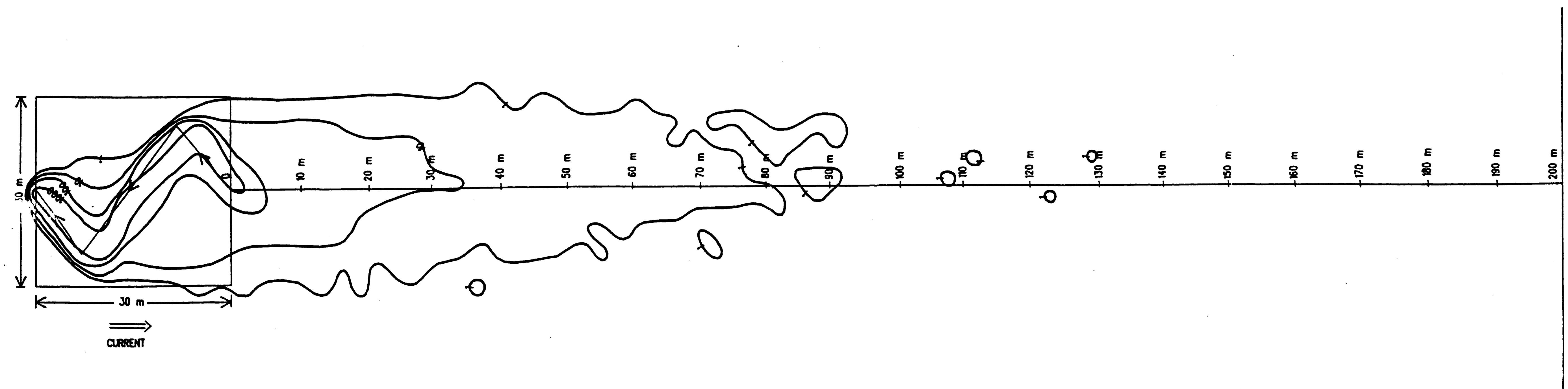


Figure 5-5. Settled concentration contours (g/sq. m).
Time = 120 minutes.
Current speed = 0.05 m/s.

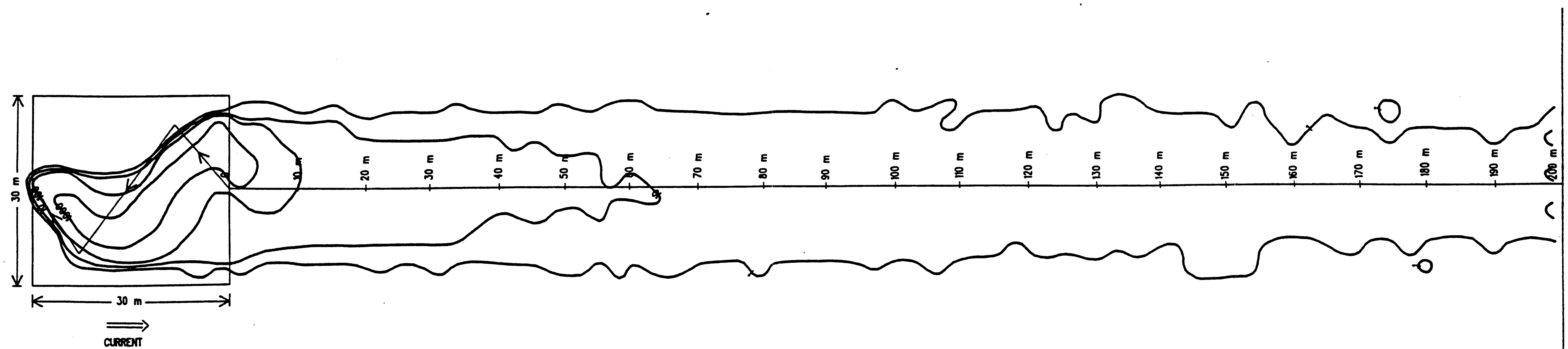


Figure 5-6. Settled concentration contours (g/sq. m).
Time = 45 minutes.
Current speed = 0.25 m/s.

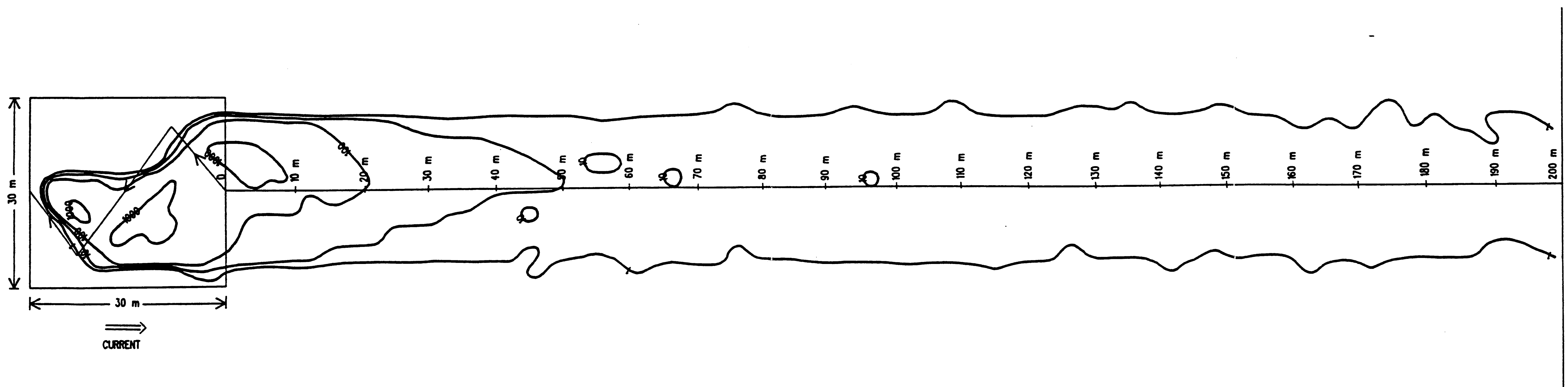


Figure 5-7. Settled concentration contours (g/sq. m).
Time = 30 minutes.
Current speed = 0.5 m/s.

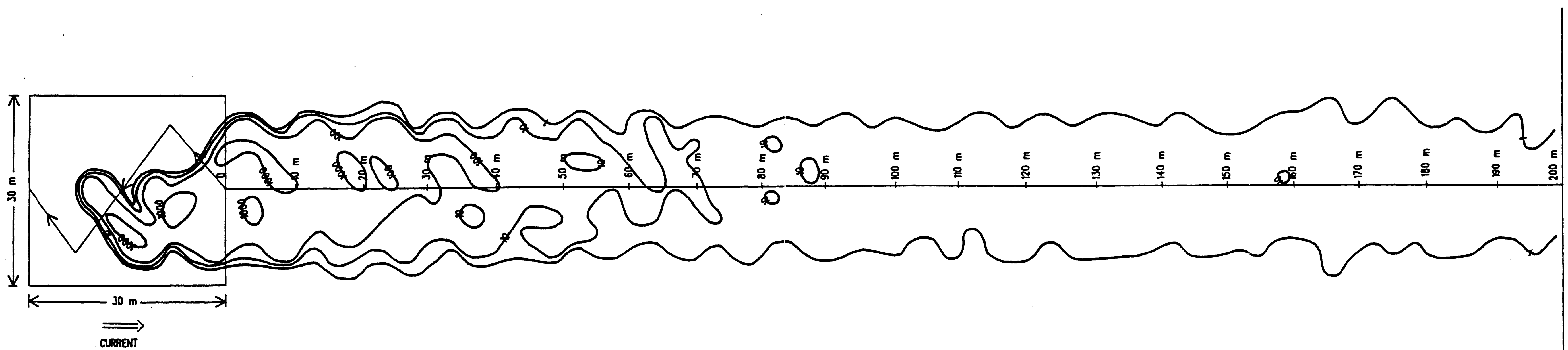


Figure 5-8. Settled concentration contours (g/sq. m).
Time = 30 minutes.
Current speed = 1.0 m/s.

seawater in the pore spaces. Using a porosity value of 0.5, which is typical of a combination of fine sand and fine sandy silty clay (Dyer, 1986), calculations yield a sediment bulk density of 1.84 g/cm^3 (R. Sternberg, personal communication). The conversion from settled concentration in g/m^2 to settled thickness in centimeters may then be carried out by simply dividing by 18,400.

The maximum settled concentration found in any of the four current speed scenarios was 3,118 g/m^2 (for 0.05 m/s), at a model output gridpoint located within 1 m of a geoduck hole. Using the above approximate technique, this maximum settled concentration equates to a maximum depositional thickness of only 0.17 cm (1.7 mm). Area average settled concentrations and thicknesses for each current speed were computed by dividing the total mass of sediment settled by the affected area, which is defined as the area encompassing all model output gridpoints exhibiting non-zero values. The results of these calculations are presented in Table 5-1. The area average settled concentrations and thicknesses were extremely small and of the same order of magnitude for each of the four current speeds. Implications of these results with respect to cumulative effects over longer time periods will be discussed in Section 5.4.4.

5.4.3 Shoreline Deposition

As may be seen in Figures 5-1 through 5-8, for the worst case in which the current is pointed directly onshore, some small amount of suspended material would reach the shoreline 200 m from the harvesting area. Using the model results, we calculated the amount of material that would be available for deposition in the intertidal zone per 100 m of shoreline, per hour of geoduck harvesting. In this calculation, we assumed that all of the available material will be deposited in the intertidal zone during a tidal cycle. In order to estimate the area of the intertidal zone, we assumed a beach slope of 1:10 and a tidal range of 4 m. For a shoreline length of 100 m, this yields a total intertidal area of 4020 m^2, slightly less than 1 acre. The results of the deposition calculation are shown in Table 5-2. As the table shows, the resulting thicknesses of material deposited in the intertidal zone per hour of harvesting are extremely small. Implications of these results with respect to cumulative effects over longer time periods will be discussed in the next section.

Table 5-1. Average settled sediment concentration and thickness over the affected area[1/]. Assumes 25 holes dug over a 20 minute duration.

Current Speed (m/s)	Affected Area (m^2)	Total Mass (kg) Settled in Area	Area Average Concentration (g/m^2)	Area Average Thickness (cm)[2/]
0.05	7,047	499.68	70.9	0.0039
0.25	6,660	494.94	74.3	0.0040
0.50	6,246	488.14	78.2	0.0043
1.00	5,427	478.97	88.3	0.0048

1/ Affected area is defined by the area encompassing all model output gridpoints exhibiting non-zero values.

2/ Assumes sediment bulk density of 1.84 g/cm^3.

Table 5-2. Material available for deposition in the intertidal zone per 100 m of shoreline per hour of geoduck harvesting[1/].

Current Speed (m/s)	Mass of Sediment (kg) Per Hour Per 100 m Shoreline Available for Deposition	Area Average Thickness (cm)
0.05	3	0.00004
0.25	46	0.0006
0.50	107	0.001
1.00	189	0.003

1/ Assumes the following: 75 holes dug per hour in a 30 m x 30 m area; harvest tract is 200 m from shore; current is directly onshore; beach slope is 1:10; tidal range is 4 m; all available material is deposited; bulk sediment density = 1.84 g/cm^3.

5.4.4 Cumulative Effects

Cumulative effects on the physical environment due to geoduck harvesting are difficult to quantify using the modeling results described above, because of the small spatial and temporal scales associated with the plumes. A simple and conservative approach, however, is to simply scale the modeling results upward by a factor that would approximate the harvesting intensity over a given area during the course of a year. The EIS states that approximately 10,000 holes per acre are dug annually on an average commercial geoduck bed. The 30 m x 30 m harvesting area we modeled equates to 900 m^2, or roughly 1/4 acre. Therefore, 2,500 holes in that area would approximate the typical hole density over the course of a year. Since 25 holes were dug in each of our simulation runs, scaling the settled concentrations (or thicknesses) by a factor of 100 would provide a worst-case estimate of long-term cumulative effects. Applying this factor to the area average thicknesses given in Table 5-1 yields area average cumulative thicknesses of approximately 0.4 cm. The EIS gives a numerical estimate of 0.02 cm for the thickness of material that would result if all the fine material released from 10,000 holes per acre were to resettle on the tract. The 0.4 cm and 0.02 cm values are not inconsistent, considering that the 0.4 cm thickness incorporates all grain sizes, not just the fines released. In any case, the depositional thickness is extremely small.

The same factor of 100 can be applied to the intertidal zone depositional thicknesses presented in Table 5-2. Again, even with an increase of two orders of magnitude, the worst case depositional thickness in the intertidal zone would be inconsequentially small.

In the above cumulative estimates, it is assumed that all of the material deposited stays in place, and cumulative deposition would be simply additive over time. In reality, this assumption will not be valid during certain times and in certain locations in Puget Sound, due to current and wave forces governing the process of sediment resuspension. These effects are discussed further in Section 6.0.

5.4.5 Applicability of Results to Other Sites in Puget Sound and Hood Canal

In general terms, it can be said that similar physical processes tend to operate in similar physical environments. To the extent that one site resembles another in terms of the physical environment (shoreline morphology, bottom sediment composition, current and wave climates), model results generated for the two sites should be correspondingly similar.

The GEODUCK model was calibrated using field data collected on the Nisqually Reach tract. However, the model was specifically designed to be nonrestrictive in its application; that is, flexibility in user input allows the model to be used in a variety of different environments. The two primary site-specific pieces of information that would be required to apply the model at some other site in Puget Sound are the bottom sediment composition (grain size distribution) and the tidal current speed.

Historical data on bottom sediment composition for many areas in Puget Sound and Hood Canal were summarized by Roberts (1974). Other bottom sediment data have been collected by WDF and other state agencies. These sources may or may not provide actual site-specific data for commercial geoduck harvest tracts. Ideally, sediment composition data collected on an actual harvest tract (or proposed tract) should be used for model input.

Current speeds at locations away from official tidal current prediction points are difficult to estimate. Published tidal current charts may be of some use in this regard. Onsite measurements would of course be preferable. Where uncertainty exists, the model can be used to examine effects associated with a range of current speeds.

6.0 RESUSPENSION OF UNCONSOLIDATED BOTTOM SEDIMENT

The sediment that settles out of the plume will initially be in an unconsolidated form. As time progresses, its water content will decrease, and its shear strength and resistance to erosion will gradually return to the initial state. The time scale over which this reconsolidation will occur is uncertain. However, in laboratory experiments with fine-grained marine sediment, Southard et al. (1971) determined that the resistance to resuspension, as indicated by the threshold erosion velocity, tends to double in time periods on the order of 12 hours. The evidence suggests, therefore, that redeposited material will tend to regain its original shear strength within one or two days, assuming that there is no further disturbance during that time.

During the period in which the sediment remains unconsolidated, it will be subject to resuspension by current and wave forces. Once resuspended, it will be available for further transport and subsequent redeposition in areas farther from its original source. However, wave and current energy responsible for such resuspension is highly dispersive, and will tend to spread and dilute the material over a much wider area than the original deposition zone, thus reducing the net areal concentrations.

A number of useful semi-empirical formulations for resuspension due to currents and waves can be found in the literature. Miller et al. (1977) provide a relationship between grain size in naturally consolidated sediment and threshold current speed that can be represented by a simple graph (Figure 6-1). Looking at the fine grain sizes of greatest interest in the present study (less than 63 microns), it can be seen that particle erosion will likely occur for current speeds greater than about 0.28 m/s. This is within the typical range of tidal current speeds encountered on geoduck beds. Therefore, we can conclude that resuspension of fine sediment deposited out of the plume associated with geoduck harvesting is possible, depending on the current regime at a particular site.

Surface wave energy is associated with oscillatory water movement at depth. Komar and Miller (1975) developed a technique for relating grain erosion thresholds for various grain sizes to water depth, wave height, and wave period. Their formulation can be presented in graphical form, as shown in Figures 6-2 (a and b). Figure 6-2(a) shows that for 2-second waves (frequently occurring on Puget Sound), resuspension of even fine particles on the bottom due to wave energy will be unlikely if the water depth is greater than about 4 m. Figure 6-2(b) (note the different scale for water depth) depicts the wave-

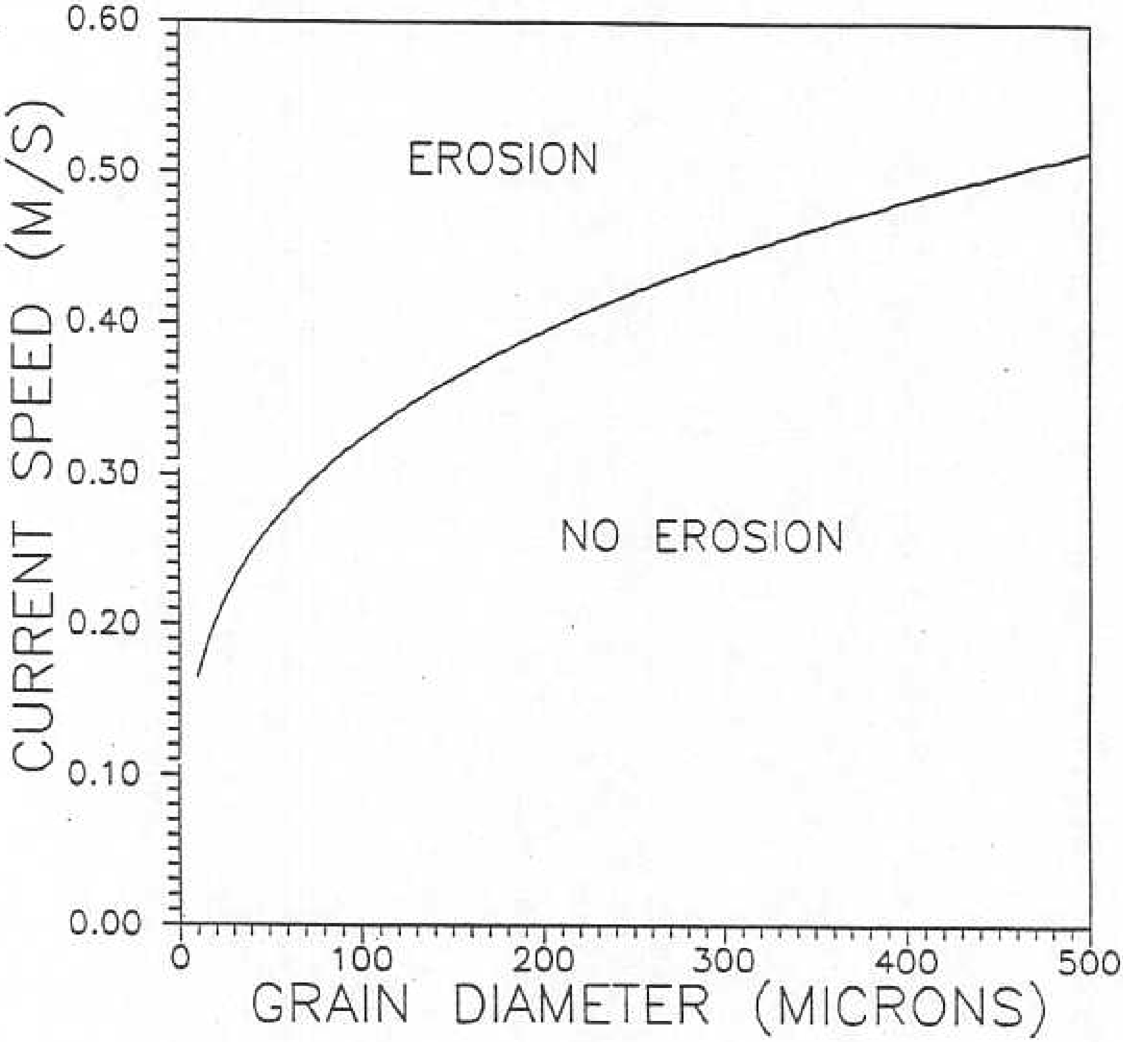
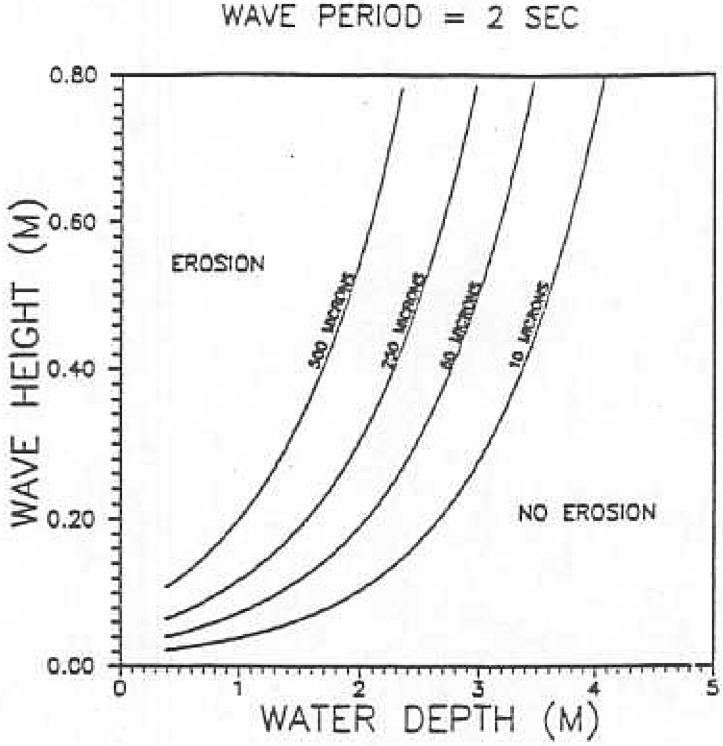


Figure 6-1. Sediment erosion threshold under unidirectional currents.

(a)



(b)

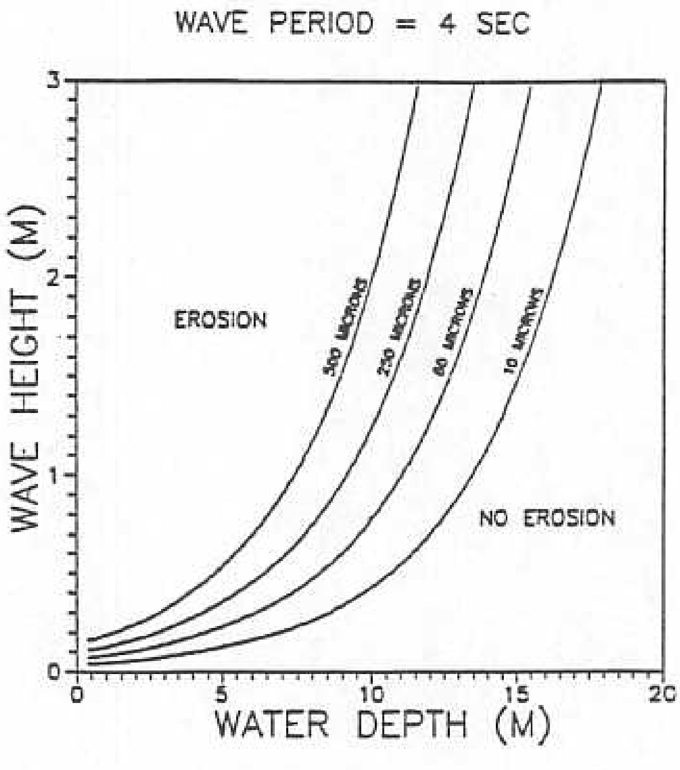


Figure 6-2. Sediment erosion threshold as a function of grain size, water depth, and wave height for wave periods of (a) 2 seconds, and (b) 4 seconds. Note the different water depth scales in the two figures.

related erosion thresholds for 4-second waves (less frequent, storm-induced waves on Puget Sound). To illustrate, for a water depth of 10 m, resuspension of fine particles will tend to occur for wave heights in excess of about 0.8 m. Depending on the location, such wave heights are possible in Puget Sound during strong wind events. As the water depth decreases, the threshold wave height for resuspension will also decrease, and thus tend to occur more frequently. As was the case with resuspension due to currents, we conclude that resuspension of unconsolidated bottom sediment due to waves is possible, and is site- and time-dependent in the Puget Sound region.

7.0 BEACH DEPOSITION AND EROSION

In Section 5.4.4, we showed that a small amount of suspended sediment resulting from geoduck harvesting may reach the shoreline and be available for deposition. In that section, we conservatively assumed that all of the available material would be deposited in the intertidal zone. In reality, the tendency for particulate matter to be deposited or eroded from beach zones is strongly dependent on the particle size and wave climate of the site. Most beaches along Puget Sound are composed of sand or gravel, suggesting that the typical wave climate is inconsistent with deposition and retention of fine sediments.

To quantify the likelihood of beach deposition, we prepared some graphs using a technique described in USACOE (1984). This technique relates wave height, wave period, and particle grain size to a dimensionless fall time parameter, called F_0, that is an indicator of the tendency for deposition or erosion to occur. Figure 7-1 (a and b) shows the results for the same wave periods (2 and 4 seconds) used previously in Figure 6-2. In these plots, the dashed vertical line corresponding to $F_0=1$ delineates the boundary between conditions under which deposition and erosion will occur. These plots illustrate a rather striking result: that for typical wave conditions in Puget Sound, deposition of fine sediment (less than 63 micron grain size) will virtually never occur if any wave energy is present. Deposition of fines on a beach will only occur in the complete absence of any wave energy. In these plots, deposition is seen only for medium and fine sand particles, and even then only under very low wave conditions.

In Section 5.4.4, our calculations based on model runs showed that the amount of material that could be deposited in the intertidal zone under worst case conditions would be extremely small. The results shown in Figure 7-1 indicate that even such insignificant deposition would be highly unlikely.

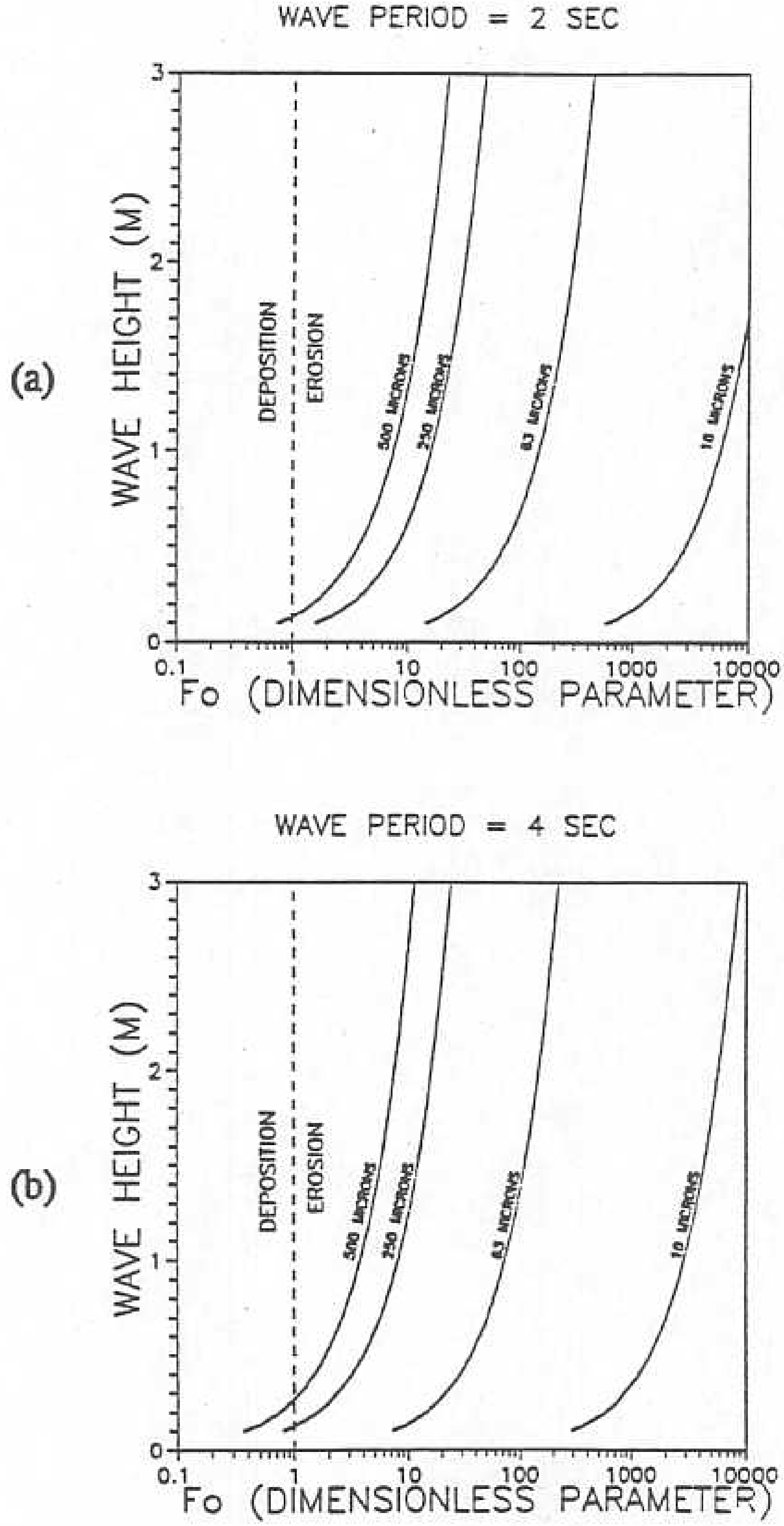


Figure 7-1. Beach deposition and erosion threshold as a function of grain size and wave height for wave periods of (a) 2 seconds, and (b) 4 seconds.

8.0 SUMMARY AND CONCLUSIONS

8.1 REVIEW OF THE EIS AND OTHER EXISTING INFORMATION

Our review of the EIS sections dealing with impacts to the physical environment identified some omissions of pertinent subject matter and some numerical inconsistencies. However, it is our finding that these deficiencies are not sufficiently serious to invalidate the overall conclusions stated in the EIS regarding physical impacts.

Very little reference material exists specifically relating to the transport and fate of suspended sediment associated with geoduck harvesting. Research on physical impacts due to hydraulic clam harvesting, while providing a worst case analogy to geoduck harvesting effects, cannot be directly applied due to the much more invasive nature of the hydraulic harvesting method. It is worth noting, however, that the research on hydraulic clam harvesting identified no significant impacts related to water quality or sedimentation.

Our focused literature search identified no pertinent references that were not cited in the EIS. Moreover, we did not find any pertinent references that have been published since the EIS was issued in 1985.

8.2 MODELING OF PLUME TRANSPORT AND FATE

We developed, tested, calibrated, and applied a numerical particle transport model (GEODUCK) to simulate the behavior of the suspended sediment plumes associated with geoduck harvesting. The model simultaneously accounts for the physical processes of advection, dispersion, and settling. The model was designed to allow the user maximum flexibility in specifying input parameters so that a wide variety of environments can be simulated. Model output includes horizontal distributions of suspended sediment concentration in the water and settled sediment concentration on the bottom.

In the model calibration step, the model was adjusted to achieve maximum agreement (significant at the 99% confidence level) between model output and actual measurements of TSS gathered during a field experiment conducted in conjunction with an actual harvesting operation.

The model results for 20-minute harvesting simulations in a 30 m x 30 m harvest area for four different current speeds showed that as the current speed increased, the suspended sediment plume lost its integrity and became segregated into a series of discrete clouds, each corresponding to the sediment released during the digging of one hole. Also, as the current speed increased, the settled sediment was displaced farther down-current from its hole, and the depositional pattern became more irregular. Local maximum and area average bottom concentrations and associated thicknesses were found to be extremely small for the 20 minute harvesting simulations. An estimate of long-term cumulative sedimentation effects, based on scaling model results to achieve typical hole density in commercial geoduck beds, yielded results that were roughly consistent with numerical estimates presented in the EIS.

Model results also indicated that some suspended material will travel as far as 200 m down-current from the harvest area, and under worst-case (albeit highly unlikely) conditions of direct onshore transport, would be available for deposition in the intertidal zone. Under the assumption that all such material would be deposited in the intertidal zone, calculations showed that the associated depositional thickness, even considering cumulative effects, would be extremely small.

8.3 SEDIMENT RESUSPENSION AND DEPOSITION

Semi-empirical techniques obtained from the literature provided the means of assessing the likelihood of resuspension of unconsolidated bottom sediment that has settled out of the plume. The results derived from these techniques indicate that resuspension of fine sediments is possible under current and wave conditions that may occur in Puget Sound. Once such material has been resuspended, it is available for further transport and subsequent deposition at greater distances from its source substrate. However, the conditions conducive to resuspension (energetic waves and currents) will further disperse and dilute the material, reducing the concentrations and depositional thicknesses.

Laboratory studies reported in the literature have shown that fine-grained marine sediment can regain most of its shear strength within 1-2 days of deposition. Presumably, within a few days of deposition, this redeposited sediment will be no more susceptible to erosion than the original substrate.

A semi-empirical technique relating sediment grain size, wave height, and wave period to the likelihood of beach deposition shows that deposition of fine suspended sediment in the intertidal zone on Puget Sound beaches is highly unlikely.

8.4 OVERALL CONCLUSION

Upon thorough consideration of existing information, field data collected during this project, plume transport modeling results, and results from semi-empirical techniques regarding resuspension and deposition, our overall conclusion is that the transport and fate of suspended sediment associated with commercial geoduck harvesting will have minimal impacts on the physical environment in the harvest tract and adjacent areas.

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YIELD ESTIMATE FOR HORSE CLAMS IN WASHINGTON STATE

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June 6, 1996

INTRODUCTION

Two species of horse or "gaper" clams *(Tresus nuttallii and T. capax)* exist in Washington waters. The two species often coexist from the low intertidal to subtidal depths of at least 150 feet, although *T nuttallii* is more abundant subtidally than *T. capax (Campbell et al.* 1990). The two species cannot be reliably distinguished while still in the substrate. Thus, from a practical fisheries management standpoint, the two species are identical and are hereafter referred to collectively as "horse clams."

Subtidal horse clams, like geoducks, fall under the resource management mandates of both the Washington Department of Fish and Wildlife (WDFW) and the Washington Department of Natural Resources (DNR). They were fished commercially in Washington from the mid-1960s to the mid-1980s using hydraulic clam harvesters, with annual landings averaging 108,000 pounds. WDFW and DNR managers stopped the fishery in the mid-1980s due to adverse public reaction to the hydraulic harvest method, not because of any biological concerns about the sustainability of the horse clam resource. No subtidal fishery for horse clams has taken place in Washington since then.

In North America, there is market demand for horse clams as bait in the Dungeness crab fishery. An Asian market for human consumption of horse clams has also been reported (Tom Bettinger, Taylor United Seafoods, personal communication).

It is easy to harvest horse clams with the standard water jet used by commercial geoduck harvesters. Indeed, they are sometimes dug accidentally by inexperienced geoduck harvesters on commercial tracts where both clams coexist. A commercial fishery for subtidal horse clams using water jets has existed in British Columbia since 1979, with the annual landings averaging about 285,000 pounds. The B.C. fishery for horse clams is restricted to those areas open for geoduck fishing. In Washington, however, WDFW and DNR have not permitted either an incidental or directed horse clam fishery using water jets. In the case of an incidental fishery for horse clams on geoduck tracts, this policy was due to the fact that no provisions for such harvests were made in the programmatic EIS for geoducks. In the case of a directed fishery, the low market value of horse clams made such a fishery economically unattractive for the two state agencies.

This situation has recently changed. First, a new programmatic EIS for geoducks is nearing completion, and it addresses the potential for an incidental horse clam fishery on geoduck tracts. As noted above, some incidental harvest of horse clams already occurs, and these clams are currently discarded on the sea floor. Secondly, several treaty tribes have expressed an interest in fishing subtidal horse clams following the federal court decision granting them a share of the shellfish resource.

The goal of this paper is three-fold: 1) to outline the existing data sources on horse clam biomass in Washington; 2) to simulate equilibrium yields of a horse clam population over a range of harvest rates; and 3) to recommend a harvest rate strategy based on this simulation, providing specific options for its implementation.

1. EXISTING DATA SOURCES ON HORSE CLAM BIOMASS

Estimates of horse clam density and biomass are available from two sources.

A. Hardshell clam surveys performed in the 1970's by WDFW divers using a venturi dredge sampler. Horse clam biomass at 47 sites totalling 5,350 acres was estimated to be 28,832,160 pounds (Goodwin and Shaul 1978). Sites ranged as far north as Point Roberts, as far west as Port Angeles, and as far south as Dyes Inlet. Because only 47 sites were sampled, this estimate represents only a portion of the state horse clam biomass. Note also that 95% confidence intervals at most sites were equal to the biomass estimates themselves.

B. WDFW geoduck surveys, which since 1984 have noted the presence or absence of horse clams within each standard 900 ft² transect. Using this presence-absence data, horse clam density can be estimated using the "stocked quadrat" method (Scheaffer *el aL* 1986) as:

$$\lambda = -(1/a)\ln(y/n)$$

where λ = density (number of horse clams per ft^2)
a = area of an individual transect (900 ft^2)
y = the number of transacts in which horse clams were not present
n = the total number of transacts sampled

The estimated variance of density ($V(\lambda)$) is given by:

$$V(\lambda) = (1/na^2)(e^{\lambda a} - 1)$$

Such estimates of horse clam density could easily be developed for all geoduck tracts surveyed over the past decade, as well as for those surveyed in the future.

It is to be expected that such density estimates based on presence-absence data will generally be less precise than those based on actual count data. To get a feel for the precision of such estimates, the mean density of horse clams and coefficient of variation (CV) for three randomly-selected geoduck tracts was calculated. At the Wyckoff tract in south Puget Sound, where 273 transects were sampled, the mean density was 0.0007 horse clams/ft^2, with CV = 0.09. At Tala Point in central Puget Sound, where 60 transects were sampled, mean density was 0.0011 horse clams/ft^2, with CV = 0. 17. At Hood Head South in Hood Canal, where 30 transects were sampled, mean density was 0.0013 horse clams/ft^2, with CV = 0.23. CVs of this magnitude are probably acceptable for management, and lower bound estimates could be used if a more conservative estimate is desired.

Note that in order to estimate biomass, some estimate of weight per horse clam would have to be applied to the density estimates. This could be done crudely with a statewide approximation based on past survey work or, more precisely, by digging a sample of horse clams from individual tracts.

2. SIMULATION OF EQUILIBRIUM YIELD FOR HORSE CLAMS

A. The yield model

Horse clam yield was modeled using an age-structured equilibrium yield model (EY-MOD I) written by Dr. Jack V. Tagart of WDFW Marine Resources. Given a set of parameter estimates for mortality, maturity, growth, and selectivity, the model collapses the number of clams at age for all cohorts in the population to a single cohort, assumed to represent the stable age distribution of the population. Population size is based on an initial unfished spawning population, a declining exponential function of survival at age, and the Baranov catch equation. The model assumes continuous recruitment, the magnitude of which is governed by the Beverton-Holt stockrecruitment curve. Outputs of the model include estimates of equilbrium yield and spawning biomass per recruit for a range of fishing mortality rates. The model is available as a QUATTRO PRO spreadsheet (version 6.0 for Windows).

B. Parameter estimates

Natural mortality

Two methods were used to estimate the instantaneous rate of natural mortality (M) for horse clams. The first method relies on the empirical relationship between maximum age and mortality rate, described for molluscs, fish, and whales by Hoenig (1983) as:

$$\ln(M) = 1.44 - 0.982\ln(t_{max})$$

where t_{max} is the maximum age in years. The maximum age for two populations of *T. nuttallii* in British Columbia was 16 years (Campbell *et al.* 1990), so that $M = 0.28$ using Hoenig's method. In a commercial sample of both species from two previously unfished sites in British Columbia, the maximum age was 15 years for *T. nuttallii* and 17 years for *T. capax* (Bourne and Harbo 1987). Using Hoenig's method, $M =$ 0.30 and O.26 for these two populations. The oldest horse clam ever taken in British Columbia age samples was 24 years (Dr. Alan Campbell, personal communication), which produces an estimate of M = 0. 19.

M was also estimated using the catch curve method (Ricker 1975) and published age-frequency data from two previously unfished sites near Tofino, British Columbia (Bourne and Harbo 1987). For this analysis, the natural logarithm of frequency on age for *T. nuttallii* at both sites and *T. capax* at Comox Bar were regressed. Catch curve estimates of M were O.35,0.6l,and O.47.

I chose the lowest of all these estimates ($M = 0.19$) as the best (i.e., most conservative) estimate of instantaneous natural mortality rate for horse clams.

Growth

Growth of *T nuttallii* has been well documented at two sites in British Columbia by Campbell *et al.* (1990). From that study, the von Bertalanffy growth parameters for horse clams at Newcastle Island, near Nanaimo were used, ($L = 18.3$ cm, $K = 0.168$, and $t_0 = 0.51$). Growth at Newcastle Island was slower than at the second site, Lemmens Inlet, near Tofino.

Length-weight relationship

The allometric log-log equation of Campbell *et al.* (1990) for Lemmens Inlet *T. nuttallii* was converted to the format $W = aL^b$ where W is total body weight in grams, L is shell length in cm, and the constants $a = 0.073023$ and $b = 3.219001$.

Maturity

Size at sexual maturity is documented for both horse clwn species in British Columbia. Campbell *et al.* (1990) found that 50% of T *nuttallii* matured at 6.8 cm, or about 3 years, near Tofino. Bourne and Smith (1972) found that *T. capax* at Seal Island became sexually mature at about 7.0 cm. For use in the equilibrium yield model, the logistic maturity-at-length relationship of Campbell *et al.* (1990) for *T. nuttallii* was converted to a simple logistic maturity-at-age curve where $a = -2.47545$ and $b = 8.44959$.

Fishery Selectivity

At two sites in British Columbia, the smallest horse clam of either species harvested by commercial divers (n = 288 clams) was 13.9 cm (Bourne and Harbo 1987). Campbell *et al* (1990) reported that "few horse clams <10.0 cm are taken" in Canadian commercial dive fisheries, and that most clams are >15.O cm. The growth and length-weight curves predict that a horse clam measuring 10.0 cm is about 5 year old and weighs 0.27 pounds, while a clam measuring 15.0 cm is roughly 11 year old and weighs 0.98 pounds. A simple logistic curve was fit by eye such that 20% of the horse clams would be selected at 5 year, and that horse clams would be fully selected at 11 year. The best-fit parameter estimates for this curve were $a = -1.04827$ and $b = 6.669991$.

Stock-recruitment (S-R) relationship

Nothing is known about the form or steepness of the stock-recruitment (S-R) relationship for horse clams. For purposes of yield modeling, the Beverton-Holt steepness parameter A was set equal to 1.0. In other words, the customary assumption of constant recruitment at all stock sizes was made. The implications of this assumption for harvest strategies are discussed below.

3. MODEL RESULTS AND HARVEST STRATEGY RECOMMENDATION

Results of the equilibrium yield modeling for horse clams are presented below in terms of five commonly-employed constant harvest rate strategies (also known as "constant F strategies). All five of these strategies set the annual quota as a linear function of biomass, applying a constant fishing mortality rate (F) to the estimate of current biomass. Two harvest strategies based on yield per recruit analysis are described (F_{max} and $F_{0.1}$), as well as three strategies based on spawning biomass per recruit analysis ($F_{35\%}$, $F_{40\%}$, and $F_{50\%}$).

The fishing mortality rate which maximizes long-term yield (F_{max}) for horse clams was 0.33. With the Beverton-Holt steepness parameter A set to 1.0, F_{max} also maximizes yield per recruit. Under this assumption (i.e., that recruitment is totally independent of stock size), F_{max} is a very aggressive fishing policy, and is not recommended as a prudent strategy.

The $F_{0.1}$ policy is often used as an alternative to F_{max}. Like F_{max}, this policy is based on yield per recruit analysis. $F_{0.1}$ is the fishing mortality rate associated with a catch rate one-tenth of the theoretical catch rate for a virgin fishery. The $F_{0.1}$, policy represents an arbitrary "backing off" from F_{max} and Deriso (1987) has shown that, in theory at least, $F_{0.1}$ is robust for a variety of S-R relationships. For horse clams, the fishing mortality rate associated with an $F_{0.1}$ policy is 0. 19.

The other three harvest rate strategies ($F_{35\%}$, $F_{40\%}$, and $F_{50\%}$) are all based on spawning per recruit (SPR) analysis. These strategies represent the fishing mortality rates which, at equilibrium, reduce the spawning biomass per recruit to 35%, 40%, and 50% of the unfished spawning biomass, respectively.

The idea behind all SPR strategies is fairly simple: since the S-R relationship for most fish stocks is unknown, the most prudent harvest strategy is one which is robust over a wide range of likely S-R relationships. Simulations made with a range of typical life history parameters and realistic S-R functions show that yield will be close to *Maximum Sustained Yield* so long as the spawning biomass is maintained somewhere in the range of about 20 - 50% of the unfished level, regardless of the form of the of S-R relationship. Within this range, both $F_{35\%}$ and $F_{40\%}$ have been recommended as risk-averse policies in fisheries where there is adequate information to place bounds on all relevant life history parameters except the S-R relationship (Mace 1994; Clark 1993).

The equilibrium model predicts that the instantaneous fishing mortality rates for horse clams associated with $F_{35\%}$, $F_{40\%}$, and $F_{50\%}$ are 0.28, 0.23, and 0. 16, respectively. Since they incorporate maturity schedules in addition to the life history processes captured by simple yield per recruit analyses, these three policies are considered superior to F_{max} and $F_{0.1}$.

The $F_{50\%}$ harvest strategy for horse clams is recommended until more research is carried out. This recommendation is made for two reasons: 1) $F_{50\%}$, is the most conservative of the three strategies, and is therefore most appropriate given our rudimentary knowledge of horse clam life history; and 2) $F_{50\%}$ is associated with an annual exploitation rate which is roughly half of F_{max}, yet produces an equilibrium yield that is only 11% less than F_{max}.

As noted above, the recommended $F_{50\%}$ harvest strategy for horse clams is attained by fishing at $F = 0.16$. This instantaneous fishing mortality corresponds to an exploitation rate (μ) of 0.135. In other words, under the $F_{50\%}$ harvest strategy, we could sustainably take 13.5% of the estimated biomass each year.

This harvest strategy could be implemented by any number of harvest tactics. Several suggested harvest tactics follow:

A. Horse clams could be fished incidentally along with geoducks in established geoduck tracts, as is done in the British Columbia fishery. The $F_{50\%}$ strategy for horse clams would entail an allowable annual exploitation rate that is nearly seven times as high as that for geoducks. Harvested geoduck tracts are re-fished only after surveys indicate that geoduck densities have recovered to prefishing levels. Empirical studies suggest that the average recovery time for such tracts is 40 year (Goodwin 1996 in press). Based on the fact that the exploitation rate for horse clams is roughly seven times that for geoducks, we may assume that horse clam populations will recover more quickly than geoduck populations on the same tract. Thus, if horse clams were taken opportunistically on established state or tribal geoduck tracts, there is little chance of overfishing them, particularly if the annual horse clam harvest did not exceed 13.5% of a region's estimated horse clam biomass. Indeed, harvesting horse clams where they coexist with geoducks might be advantageous. Goodwin (1979, 1978) describes the aggressive recruitment of horse clams and their subsequent domination of hardshell clam beds following hardshell fishing, and suggests that the same pattern might be avoided on geoduck beds if horse clams were taken as well (Goodwin 1996 in press).

This tactic is probably preferable in most areas of the state, where horse clams and geoducks coexist on at least some geoduck tracts. It is likely that all or most of the horse clams required by the market could be taken opportunistically during regular geoduck fishing. One of the major advantages of this tactic is that no separate horse clam surveys would be required. Another advantage is that horse clams which are accidentally removed from the substrate could be legally harvested. Thus, both harvesters and the state would make money on clams that are currently wasted and unreported.

B. Horse clams could be harvested as a separate fishery in the same manner as has been proposed for geoducks under recent state/tribal agreements. That is, the horse clam biomass could be estimated in each of six regions based on the survey methods outlined above. In each region, fishers could then take 13.5% of the estimated total regional biomass on an annual basis; this annual biomass would be taken from one or a few individual tracts which had been previously surveyed by methods similar to those outlined for geoducks. In other words, the entire annual quota for a region would be taken from a few discrete tracts, and the fishery would then move the following year to newly surveyed tracts; the original tracts would not be fished again until horse clam densities have returned to pre-fishing levels.

This tactic might be the preferred option in areas of the state where subtidal tracts contain only horse clams and no geoducks (or very few geoducks), such as Neah Bay. Any geoducks taken in such tracts would have to be counted against the regional geoduck harvest share. A drawback of this tactic is that horse clam tracts would have to be surveyed prior to fishing. The economic return expected from such horse clam surveys will be much lower than for geoducks.

C. Horse clams could be fished annually from discrete, surveyed beds. Under this tactic, horse clam beds could be identified and surveyed using methods similar to those used for geoducks. Such beds could then each be fished annually at 13.5% of the estimated biomass for the given bed. The chosen beds would be fished year in and year out.

This tactic, like the one above, might be optimal in areas of the state where horse clams predominate and few geoducks are found. But it also has some obvious disadvantages. First, horse clam surveys would still have to be performed, and this may prove uneconomical. Secondly, some stock assessment would be required annually to estimate the current biomass on each bed for a constant harvest rate strategy. Alternately, a constant catch strategy could be used in lieu of annual adjustments.

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The relative abundance of benthic animals and plants on subtidal geoduck tracts before and after commercial geoduck fishing

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INTRODUCTION

The primary objective of geoduck surveys is to estimate, prior to fishing, the mean density of harvestable geoducks within a commercial tract. Survey methodology is described in detail in Bradbury *et al.* (1997), and relies on a series of strip transects which run from the shallow commercial boundary (-18 ft MLLW) to the deep commercial boundary (-70 ft). Each strip transect is 150 ft long by six ft wide (900 ft^2) , and the survey is performed by two divers swimming side-by-side. A series of such strip transects comprises a grid line, and grid lines are spaced systematically (usually every 1,000 ft apart) throughout the commercial tract being surveyed.

Divers performing these surveys count visible geoduck siphons and record their counts at the end of each strip transect. Since 1984, divers have also recorded the presence or absence of other animals and plants observed along each transect. These data are used primarily to characterize the biota of commercial tracts for pre-fishing environmental assessments. On some commercial geoduck tracts, such presence/absence data are available not only from pre-fishing surveys, but also from post-fishing dive surveys performed after commercial geoduck fishing had been completed. Here I use presence/absence data for some of the animals and plants commonly found on geoduck tracts to answer the question: Does the relative abundance of benthic animals and plants change following commercial geoduck harvest?

METHODS AND MATERIALS

I compared, at each study tract and for each plant or animal, the proportion of all 900 ft^2 transects in which the plant or animal was present *before* fishing to the proportion of all transects in which it was present *after* geoduck fishing. The null hypothesis (H_0) was that the proportions before and after fishing were equal, and this hypothesis was tested with a 2 x 2 contingency table (Zar 1984). The tabled chi-square value for $\alpha = 0.05$ and df = 1 is equal to 3.841, and values higher than this resulted in rejection of H_0.

Dive survey data from ten commercial geoduck tracts in Puget Sound were used for this analysis (Table 1, Figure 1). These particular tracts were selected from the hundreds of surveyed tracts because they were surveyed both prior to commercial geoduck fishing and surveyed again within two years of the end of fishing. Post-harvest surveys were abandoned in 1993 (because Department of Natural Resources began on-site monitoring and weigh-outs of the commercial catch), eliminating many tracts with pre-fishing data from this analysis. Some other tracts did not receive a post-fishing survey until many years following the end of fishing, making them less useful for estimating fishing-related changes to the benthic biota. Presence/absence data on benthic biota was not collected prior to 1984, eliminating from consideration most tracts surveyed during the first 17 years of geoduck management. Post-harvest surveys were conducted at a lower intensity than pre-fishing surveys, resulting in the lower post-fishing sample sizes per tract in Table 1.

Table 1. Commercial geoduck tracts used in the analysis of relative abundance of benthic animals and plants.

Tract name	Management Region	Prefishing survey date	Period of fishing	Postfishing survey date	No. pre-fishing transects	No. post-fishing transects
Anderson Cove	Hood Canal	May 1985	1985-86	October 1988	47	14
Oak Bay 2	Central Sound	May 1985	1986-87	September 1988	13	12
Indian Island South	Central Sound	May 1985	1985-86	October 1987	15	9
Kilisut 1	Central Sound	April 1985	1986-87	September 1988	27	13
Hudson Point	Central Sound	April 1985	1986-87	September 1988	103	35
Kala Pt/Old Ft. Townsend	Central Sound	April 1985	1985-86	October 1987	47	20
Middle Point	Strait	May 1985	1986-87	September 1988	86	26
Otso	South Sound	April 1987	1988-89	May, July 1989	66	38
Crane Point	Central Sound	June 1985	1986-87	September 1988	30	16
Budd Inlet	South Sound	April 1988	1989-90	June 1990	102	31

Species (or, in some cases, taxa) of benthic plants and animals included in this analysis are shown in Table 2. Not all benthic plants and animals observed during geoduck surveys are included in this analysis. Some species were present during pre-fishing surveyes on only one or two of the ten study tracts; these were not included in the analysis because it would be impossible to discern any trends with such a small sample size. Thus, the plants and animals in this analysis represent those that are most often associated with geoducks on commercial tracts. Also not considered here are plants and animals which are too small or too cryptic to be readily observed and properly identified in all situations by divers swimming rapidly along a geoduck transect. This includes many of the small bivalve molluscs (e.g., butter clams, horse mussels, cockles, and truncated mya clams, all of which are at times difficult to see and identify by siphon characteristics alone) as well as many hydroids, bryozoans, and small gastropods. Tracts were included in the analysis for a particular plant or animal if the species was present on at least one transect either before fishing *or* after fishing. One species frequently observed on the study tracts (sea cucumber, *Parastichopus californicus*) was eliminated from the analysis because the extensive commercial dive fishery for this species would likely confound any analysis of geoduck-fishing effects.

Table 2. Species or taxons included in the analysis of relative abundance of benthic animals and plants.

Common name or taxon	**Scientific name**	**Group**	**Number of tracts**
Dungeness crab	*Cancer magister*	Epifauna	7
Red rock crab	*Cancer productus*	Epifauna	8
Graceful crab	*Cancer gracilis*	Epifauna	5
Sunflower star	*Pycnopodia helianthoides*	Epifauna	10
Pink short-spined star	*Pisaster brevispinus*	Epifauna	9
Flatfish	Family Pleuronectidae	Epifauna	9
Orange sea pen	*Ptilosarcus gurneyi*	Infauna	7
Sea whip	Family Virgulariidae	Infauna	3
Plumose anemone	*Metridium senile*	Infauna	8
Tube-dwelling anemone	*Pachycerianthus fimbriatus*	Infauna	6
Polychaete tube worms	*Spiochaetopterus sp. & Phyllochaetopterus sp.*	Infauna	7
Horse (gaper) clam	*Tresus sp.*	Infauna	7
Laminarian kelp	*Laminaria sp.*	Macroalgae	8

RESULTS

Epifauna

Of the seven tracts on which **Dungeness crab** (*Cancer magister*) were observed, only one tract (Crane Point) showed a statistically significant change following geoduck fishing (Appendix Table 1). On the Crane Point tract, Dungeness crab were observed on 20% of the transects prior to fishing, and 56% following fishing. When all data from the seven tracts were combined, there was a statistically significant increase in the proportion of Dungeness crab observed following fishing (17% of transects following fishing contained Dungeness crabs, compared to 9% before fishing).

Of the eight tracts containing **Red rock crab** (*Cancer productus*), only one tract (Budd Inlet) showed a statistically significant change following geoduck fishing (Appendix Table 2). On the Budd Inlet tract, red rock crab were observed on 11% of the transects prior to fishing, and 45% following fishing. When all data from the eight tracts were combined, there was no statistically significant change following geoduck fishing.

Of the five tracts on which **Graceful crab** (*Cancer gracilis*) were observed, two tracts (Otso Point and Budd Inlet) showed statistically significant changes following geoduck fishing (Appendix Table 3). The proportion of transects containing graceful crabs increased from 20% to 87% on the Otso Point tract, and from 30% to 94% on the Budd Inlet tract. When data from all the five tracts were combined, there was a statistically significant increase observed following fishing (57% of transects following fishing contained graceful crabs, compared to 20% before fishing).

On the ten tracts on which **Sunflower stars** (*Pycnopodia helianthoides*) were observed, no statistically significant changes were observed following fishing, nor were significant changes observed when the data from all ten tracts were combined (Appendix Table 4).

On the nine tracts containing **Pink short-spined stars** (*Pisaster brevispinus*), no statistically significant changes were observed following fishing, nor were significant changes observed when the data from all ten tracts were combined (Appendix Table 5).

Of the nine tracts on which **Flatfish** (Family Pleuronectidae) were observed, only two tracts (Kilisut 1 and Hudson Point) showed statistically significant changes following fishing (Appendix Table 6). The proportion of transects containing flatfish increased from zero to 31% on the Kilisut 1 tract, and from 7% to 23% on the Hudson Point tract. When data from all the nine tracts were combined, there was a statistically significant increase observed following fishing (27% of transects following fishing contained flatfish, compared to 16% before fishing).

Infauna

Of the seven tracts containing **Sea pens** (*Ptilosarcus gurneyi*), only one tract (Kala Point) showed a statistically significant change following fishing (Appendix Table 7). The proportion of transects containing sea pens increased from zero to 25% on the Kala Point tract. When data from all the seven tracts were combined, there was a statistically significant increase observed following fishing (35% of transects following fishing contained sea pens, compared to 24% before fishing).

significant change following fishing (12 tracts exhibited increases in a species or taxon, while three exhibited decreases). One taxon (horse clams) exhibited changes on three of the study tracts, while three taxa showed changes on two of the study tracts (graceful crab, flatfish, and polychaete tube worms). Six taxa exhibited changes on a single study tract (Dungeness crab, red rock crab, sea pens, plumose anemones, tube-dwelling anemones, and laminarian kelp). Two species showed no change on any of the study tracts (sunflower star and pink short-spined star). No species or taxon exhibited statistically significant changes on a majority of the study tracts in which it was present.

These data should be interpreted with caution for two main reasons: First, because no unfished "control" sites were surveyed, it is impossible to determine causality. In some cases, we noted statistically significant changes in the relative abundance of an animal or plant following geoduck fishing; but there is no way to know from these data if the change occurred *as a result* of geoduck fishing, or due to some other cause. Many of the animals and plants in this study exhibit significant shifts in abundance in the absence of geoduck fishing. Thus, significant post-fishing changes noted during this study in Washington could be mistakenly ascribed to geoduck fishing. Conversely, natural (i.e., non-fishing related) shifts in abundance might have obscured the real effects of geoduck fishing in this study.

The second caveat in data interpretation owes to the fact that only the *presence* of a particular animal or plant within a transect was noted, rather than an actual count. Presence/absence data can lead to valid estimates of density, and the technique is commonly used in forestry, wildlife management, and microbiology ("stocked-quadrat" or "frequency-index" methods; Scheaffer *et al.* 1986; Seber 1982; Cochran 1950). Density estimates could have been made for all animals and plants in this study, but these would be superfluous for the comparison of before- and after-fishing changes (i.e., the results would be identical whether comparing density or relative abundance). But density estimates from presence/absence data are rarely as precise as those based on actual counts, and the results reported here suffer from the same imprecision. Therefore, the statistical power of the contingency table tests used to detect changes following fishing is relatively low, increasing the probability of a Type II error (i.e., finding no effect when an effect occurred).

In summary, few statistically significant changes in the relative abundance of the animals and plants considered in this study were detected a year following geoduck fishing. Most (80%) of the few changes which were detected after geoduck fishing involved an increased abundance of animals or plants. These increases may have been due to geoduck fishing (related perhaps to increased availability of food or space), or may have been due to natural, non-fishing related cycles of abundance or migration.

Acknowledgements

Don Rothaus and Lynn Goodwin participated with the author on most of the post-harvest dives. Michael Ulrich provided the map and performed all the database analyses. Bob Sizemore reviewed an earlier draft.

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The effect of commercial geoduck (*Panopea abrupta*) fishing on Dungeness crab (*Cancer magister*) catch per unit effort in Hood Canal, Washington

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INTRODUCTION

Geoduck clams (*Panopea abrupta*) dominate the biomass of benthic infaunal communities in many parts of Puget Sound, Washington, and support an important commercial fishery (Goodwin and Pease 1989). Since 1971, divers have commercially fished geoducks in Washington by individually extracting them from the substrate with high-pressure water jets. Various crab species, including the large and commercially important Dungeness crab (*Cancer magister*) are common on many geoduck beds north of Vashon Island in Puget Sound (unpublished Washington Department of Fish and Wildlife [WDFW] dive survey data). Recreational crab pot fishing also occurs on some of these geoduck beds, and some crab fishers have complained that their crab fishing success declines following commercial geoduck harvest.

The objective of this study was to determine if there was a significant effect of commercial geoduck fishing on Dungeness crab fishing catch-per-unit-effort (CPUE). We sampled crabs using baited pots at one site before, during, and after commercial geoduck fishing. Concurrently, we sampled crabs at a nearby unfished site. Both sites were sampled 20 times over a period of 4.6 years. Specifically, we wanted to determine if significant changes in crab CPUE occurred following geoduck fishing in the treatment site, and if any such changes could be attributed to geoduck fishing.

METHODS

Experimental Design

Two sites, a treatment site and a control site, were experimentally fished with crab pots in order to determine if geoduck fishing had an effect on Dungeness crab fishing success. The observed random variable was crab CPUE, the number of crabs caught per pot. The treatment site was sampled both before and after commercial geoduck fishing in order to test the primary null hypothesis: H_0: $\mu_{before} = \mu_{after}$, where μ_{before} = mean CPUE of all pre-fishing samples, and μ_{after} = mean CPUE of all post-fishing samples.

Crab CPUE at the treatment site could be affected both by fishing effects (the direct or indirect consequences of geoduck fishing) and non-fishing effects (environmental, seasonal, or crab behavioral effects not related to geoduck fishing). Non-fishing effects at the treatment site might mask the effects of geoduck fishing, causing acceptance of H_0 and a Type II error. Conversely, non-fishing effects at the treatment site might be mistaken for fishing effects, causing rejection of H_0 and a Type I error. Thus, an unfished control site was sampled concurrently with the treatment site in order to account for non-fishing effects affecting crab CPUE.

This comparison between control and treatment sites assumed that crab CPUE at both sites was equally affected by non-fishing effects. This assumption and other hypotheses had to be tested prior to a test of H_0 at the treatment site, as outlined in the sequence below:

Step 1. Test the assumption that crab CPUE at the control site and treatment site are equally affected by non-fishing effects.

This assumption was tested with a test on the correlation coefficient ρ (Sokal and Rohlf 1981). Specifically, we tested the hypothesis that $\rho > 0$, with the variables x_i = estimated CPUE at the control site for the i = 1-10 pre-fishing samples, and y_i = estimated CPUE at the treatment site for the i = 1-10 pre-fishing samples. If $\rho \leq 0$, then correlation was either nonexistent or negative, implying that the control site was not a reliable analog of the treatment site in terms of non-fishing effects. Without being able to "tease out" non-fishing effects at the treatment site, we would be unable to determine if fishing effects had occurred, and the experiment would be terminated. If, on the other hand, $\rho > 0$, we could conclude that the two sites were positively correlated, and that therefore the control site was a reliable estimator of non-fishing effects at the treatment site. However, $\rho > 0$ does not necessarily imply strong correlation. Therefore we established an arbitrary guideline for "strong" correlation and tested the hypothesis that $\rho \geq 0.70$. If we failed to reject this hypothesis,we continued to Step 2.

Step 2. Test whether non-fishing effects differed during the pre-fishing and post-fishing periods.

Following acceptance of the assumption that the control and treatment sites are equally affected by non-fishing effects (Step 1), the control site provides a basis for this test, since no fishing occurred there during either period. We can test the hypothesis H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where μ is mean crab CPUE at the control site. If H_0 is not rejected, no significant changes occurred, and we proceed to Step 3. If, on the other hand, H_0 is rejected, then a significant change due to non-fishing effects occurred at the control site between the two time periods which must be taken into account at the treatment site, and we proceed to Step 4.

Step 3. Failing to reject H_0 in Step 2, we would conclude that there are no changes in non-fishing effects between the pre- and post-fishing time periods. In this step we can then proceed to directly test whether CPUE changed in the treatment area following geoduck fishing, and significance will imply an effect due to geoduck fishing rather than environmental, seasonal, or behavioral effects. We test the primary hypothesis, H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where μ is the mean crab CPUE at the treatment site. Rejection of H_0 would imply an effect due to geoduck fishing.

Step 4. Rejecting H_0 in Step 2, we would conclude that there are significant changes in non-fishing effects between the pre- and post-fishing time periods which must be accounted for in hypothesis tests of the treatment site. As in Step 3, we again test the primary hypothesis, H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where μ is the mean crab CPUE at the treatment site, but we now require a modification of the means test in order to "tease out" the significant changes due to non-fishing effects.

We first followed the above testing sequence using the estimated CPUE of all Dungeness crabs. Then we performed the sequence again, using only the estimated CPUE of Dungeness crabs which may be legally taken by sport and commercial crabbers (i.e., male Dungeness crabs with a carapace width > 151 mm).

Site Description

Two sites along the western shore of northern Hood Canal were chosen for the experiment (Figure 1). Thorndyke Bay, located at 47° 48' 22" N 122° 44' 15" W, was chosen as the treatment site because a commercial geoduck harvest was scheduled to start there in August 1992. Commercial divers landed 1.8 million pounds of geoducks from the treatment site during the period of this experiment. South Point, located at 47° 49' 27" N 122° 41' 57" W, was chosen as the unfished control site because of its proximity to Thorndyke Bay, which lies about 1.8 km to the south. South Point was surveyed by WDFW divers in 1986, but has never been fished commercially for geoducks.

WDFW geoduck dive surveys in 1986 and 1990 indicated that Dungeness crab occurred at both sites. During these surveys, divers at the treatment site (Thorndyke Bay) sighted Dungeness crabs on 12% of all transects. At the control site (South Point), divers sighted Dungeness crabs on 17% of the transects. Neither site was fished commercially for crabs during the course of this experiment. Both sites are open for recreational crab fishing, and recreational crab pots were observed at both sites during portions of the study. Substrate at both sites is comparable, a mix of roughly equal parts sand and mud, and is typical of commercial geoduck beds.

Each of the two sites was divided into a northern half and a southern half to facilitate the use of 30 crab pots over a two-day sampling period as described below. Distance between the northern and southern portions of each site was approximately 30 m. Total area of the control site (northern and southern halves combined) was roughly 16,700 m^2. Total area of the treatment site (northern and southern halves combined) was roughly 33,400 m^2. The difference between the areas of the two sites was due to differences in bottom contours; the length of each site (i.e., the distance along the shoreline) was identical, but because crab pots were placed along depth contours (see below), the more gently sloping bottom contour at the treatment site increased its width (i.e., distance from the shoreline) relative to the control site.

Crab Sampling Methods

Both the control and treatment sites were sampled for crab CPUE over a period of 4.6 years, from December 1990 through July 1995. During this period, each of the two sites was sampled on 20 occasions, and both of the two sites were sampled on the same days. Sampling dates are shown in Table 1.

The first ten samples at both sites were taken prior to any geoduck fishing. Commercial geoduck fishing began at the treatment site in August 1992. No geoduck fishing occurred at the control site, either before or during this experiment.

At the treatment site, the commercial geoduck fishery took place during two distinct seasons, from August 1992 through December 1992, and from June 1993 through December 1994. During the five-month period from January 1993 through May 1993, geoduck fishing was closed in the treatment site. For purposes of this analysis, we considered all samples taken after the commercial geoduck fishing began in August 1992 to be "post-fishing" samples. Thus, "post-fishing" samples included three samples taken during the first fishing season, two during the five-month hiatus between fishing seasons, and two during the second fishing season. Thus, there were ten pre-fishing samples spanning 1.6 years, and ten post-fishing samples spanning 3.0 years. Note that we use the term "post-fishing samples" for simplicity's sake when referring to both the treatment and control sites, although no fishing took place in the control site.

Each sample consisted of three consecutive days during which crab pots were set and retrieved. On the first day, 15 commercial crab pots were set in the northern half of each site and allowed to soak overnight for an average of 22 hrs. At each site, five of the 15 pots were set at -20 ft MLLW, five were set at -40 ft MLLW, and five were set at --55 ft MLLW. This depth range was chosen because the commercial geoduck fishery takes place between -18 ft MLLW and -70 ft MLLW. Along each of these depth contours, the five pots were positioned roughly 30 m apart. Each pot was baited with about 0.7 kg of frozen geoduck meat. On the second day of each sample, the pots were pulled at each site and the crabs caught were sampled and released. Pots were then re-baited and reset in the southern half of each site, along the same depth contours and with the same approximate spacing. Following a second overnight soak which averaged 22 hours, the pots were again recovered, and the crabs sampled and released. Bait removed from pots following fishing was always kept aboard and discarded well away from the test sites.

During some of the sampling, stormy weather or equipment problems prevented timely collection of some crab pots. This resulted in some pots soaking for a longer time than others. In such cases, we eliminated these pots from data analysis.

To avoid conflicts with the commercial geoduck fishing fleet, all samples taken during the two fishing seasons were made during the weekends, when the fishery was closed.

The crab species, sex, carapace width, and shell condition (new molt, soft shell, hard shell, old shell) were noted for each crab caught. In addition, the presence or absence of external embryos was recorded for all female crabs. Individual crab weights were taken during eight of the samples.

RESULTS

Table 1 and Figures 2 and 3 show how the estimates of Dungeness crab CPUE varied at the control and treatment sites during the 4.6 years of the experiment. Estimated CPUE for total Dungeness crab was higher at the control site than at the treatment site throughout the pre-fishing period (unpaired t-test of equality of means assuming equal variance, $t = 3.86$, $\alpha = 0.05$, df = 18, $P = 0.0012$, two-tailed test; F-test of equality of variances, $F = 3.179$, $\alpha = 0.05$, df = 9,9). Estimated CPUE for total Dungeness crab was not significantly higher at the control site than at the treatment site throughout the post-fishing period, however (unpaired t-test of equality of means assuming equal variance, $t = 1.81$, $\alpha = 0.05$, df = 18, $P = 0.0867$, two-tailed test; F-test of equality of variances, $F = 1.807$, $\alpha = 0.05$, df = 9,9).

Mean estimated CPUE at the treatment site prior to geoduck fishing was 1.70 Dungeness crabs/pot, and was 2.96 crabs/pot during the post-fishing period. At the control site, mean estimated CPUE prior to fishing was 4.79 crabs/pot, and post-fishing estimated CPUE was 4.85 crabs/pot. When only legal crabs (males > 151mm carapace width) were considered, mean pre-fishing and post-fishing estimated CPUEs at the treatment site were 1.24 and 2.31 crabs/pot, respectively. At the control site, mean pre-fishing and post-fishing estimated CPUEs for legal crabs were 3.20 and 3.53 crabs/pot, respectively.

The first assumption to be tested in Step 1 of the experimental design was that the control and treatment sites were equally affected by seasonal and environmental variables. This assumption was examined with a test on the correlation coefficient ρ (Sokal and Rohlf 1981). Specifically, we tested the null hypothesis H_0: $\rho = 0$, where x_i = estimated Dungeness crab CPUE at the control site for the i = 1-10 pre-fishing samples, and y_i = estimated Dungeness crab CPUE at the treatment site for the i = 1-10 pre-fishing samples. The null hypothesis of no correlation was rejected (r = 0.8339, α = 0.05, df = 8, P = 0.0010). A non-parametric correlation test also demonstrated a statistically significant correlation between control and treatment sites during the pre-fishing period (Spearman rank test, r_s = 0.806, α = 0.05, n = 8, P = 0.0032). We performed the same two tests on CPUE data for legal Dungeness crabs and got similar results (r = 0.8738, α = 0.05, df = 8, P = 0.0003; r_s = 0.818, α = 0.05, n = 8, P = 0.0023). We used Fisher's transformation (Zar 1984) to set confidence limits on the estimate of ρ for total Dungeness crab at the control and treatment sites. The asymmetric 95% confidence bounds on the estimate r (= 0.8339) were $0.4301 < r < 0.9595$. Based on the rejection of H_0 in these correlation tests and a lower confidence bound on ρ that is not unreasonably low, we were willing to accept the first assumption of equal non-fishing effects in the control and treatment sites.

Next, we proceeded to Step 2 and tested whether crab CPUE differed in the control site before and after geoduck fishing in the treatment site. Specifically, we tested the null hypothesis H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where $\mu_{pre\text{-}fishing}$ is the mean crab CPUE (number of total Dungeness crab/pot) during the pre-fishing period at the control site, and $\mu_{post\text{-}fishing}$ is the mean CPUE during the post-fishing period at the control site. Variances about the two estimated mean CPUEs were not significantly different (F-test, F = 1.258, α = 0.05, df = 9,9), so an unpaired t-test assuming equal variance was used to test the equality of the two means. There was no statistically significant difference between pre- and post-fishing periods (unpaired t-test with equal variance, t = -0.06, α = 0.05, df = 18, P = 0.95, two-tailed test). We performed the same test with CPUE data for legal Dungeness crabs and got a similar result (F-test, F = 1.749, α = 0.05, df = 9,9; unpaired t-test with equal variance, t = -0.45, α = 0.05, df = 18, P = 0.66, two-tailed test). These results suggest that there were no non-fishing effects occurring in the control area which would have to be "teased out" of the treatment area in the post-fishing period. In other words, we could assume that statistically significant changes following fishing in the treatment area, if any, could be attributed to geoduck fishing and not environmental "noise."

Thus, we proceeded to Step 3 and tested the primary hypothesis, whether crab CPUE in the treatment site differed following geoduck fishing. Specifically, we tested the null hypothesis H_0: $\mu_{pre\text{-}fishing} = \mu_{post\text{-}fishing}$, where $\mu_{pre\text{-}fishing}$ is the mean crab CPUE (total Dungeness crab/pot) during the pre-fishing period at the treatment site, and $\mu_{post\text{-}fishing}$ is the mean CPUE during the post-fishing period at the treatment site. Variances about the two mean CPUEs were significantly different (F-test, F = 4.560, α = 0.05, df = 9,9), so an unpaired t-test assuming unequal variance was used to test the equality of the two means. There was no statistically significant difference in crab CPUE between pre- and post-fishing periods at the treatment site (unpaired t-test with unequal variance, t = -1.36, α = 0.05, approximate df = 12, P = 0.20, two-tailed test). The same tests were performed using CPUE data for legal Dungeness crab with similar results (F-test, F = 3.709, α = 0.05, df = 9,9; unpaired t-test with equal variance, t = -1.59, α = 0.05, df = 18, P = 0.13, two-tailed test).

By failing to reject H_0 in Step 3, we concluded that there were no significant effects on crab CPUE which could be attributed to geoduck fishing at the treatment site in Thorndyke Bay.

We estimated the statistical power (1-β) of the experiment using CPUE data for total Dungeness crabs at both the control and treatment sites. First, we estimated the power of the two-sample t-test at the control site to detect a change in mean CPUE of ± 50%. We assumed sample sizes $n_1 = n_2 = 10$ as in our experiment, and $\alpha = 0.05$ (two-tailed), and used the power test outlined in Zar (1984). Since mean CPUE at the control site throughout the experiment was 4.82 crabs/pot, we were therefore estimating the probability of detecting a true difference of ± 2.41 crabs/pot from this mean level. A value of $\phi = 1.82$ and $\nu = (n_1 + n_2) - 2 = 18$ was associated with a power (1-β) of about 0.65. Thus, our experiment had only a 65% chance of detecting a 50% change (either an increase or a decrease) in total Dungeness crab CPUE at the control site.

Similarly, we estimated the minimum difference in mean CPUEs at the control site which we would detect with a power of 0.90, given the sample sizes above and $\alpha = 0.05$. The minimum difference which we would have a 90% chance of detecting was 3.22 crabs/pot. Since the mean CPUE at the control site during the entire experiment was 4.82 crabs/pot, CPUE would have to increase or decrease at least 67% before we would have a 90% chance of detecting it with our experimental methods.

We also estimated power of the two-sample t-test at the treatment site. The power of the test to detect a change in mean CPUE of ±50% was almost zero at the $\alpha = 0.05$ significance level. The minimum difference in mean CPUE that would be detected with a power of 0.90 was 3.00 crabs/pot. Mean CPUE at the treatment site prior to geoduck fishing was 1.70 crabs/pot, so the minimum detectable difference amounts to 176% of the average CPUE.

The same power tests were performed using CPUE data for legal Dungeness crab with similar results. The power (1-β) of the two-sample t-test to detect changes in mean CPUE for legal Dungeness crabs of ±50% at the control site was 0.55. The minimum difference in mean CPUEs at the control site which we would have a 90% chance of detecting was 2.54 legal crabs. Since the mean CPUE at the control site during the entire experiment was 3.36 legal crabs/pot, CPUE would have to increase or decrease at least 76% before we would have a 90% chance of detecting it with our methods. At the treatment site, power of the test to detect changes of ±50% in legal Dungeness CPUE was almost zero, and the minimum detectable difference with a power of 0.90 was 189% of the average pre-fishing CPUE.

DISCUSSION

This study tested the effects of geoduck fishing on crab CPUE (i.e., the number of crab per pot), not on the absolute abundance or density of crabs. Although crab CPUE may be a valid estimator of crab abundance or density, we did not make this assumption nor test it. Confining our results to crab CPUE in this way is appropriate, because the impetus for this experiment was the frequent complaint of recreational crabbers that their catch rate (i.e., the number of crabs per pot) declines following commercial geoduck fishing. Estimating CPUE with crab pots as we did is perhaps more relevant to the question posed by recreational crabbers than attempting to directly estimate crab abundance or density. Indeed, we can construct plausible scenarios whereby crab CPUE could be altered by geoduck fishing due to crab feeding behavior changes, even as abundance or absolute density of crabs in the area remains stable. Our results, however, suggest that there is no statistically significant change in CPUE following geoduck fishing.

Implicit in our experimental design were several assumptions which could not be statistically tested. The first of these assumptions was that crabs caught during each sample represented a random sample of the crab population, and were independent of previous samples. The average time between two samples was 88 days, and the minimum time between samples was 28 days. Crabs are highly mobile, moving in search of food and migrating due to reproductive and molting cues. Cleaver (1949) reported that tagged crabs released at Grays Harbor, Washington, traveled an average of 14 km in three months, which was the average time between samples in this study. The combination of crab motility and a lengthy period between samples tends to support our assumption that crabs randomly mixed in the population between sampling occasions.

A second related assumption is that handling mortality of crabs was negligible during the experiment, or else equal at both sites. Dungeness crabs, except when soft-shelled immediately following a molt, are not easily harmed by normal handling. In any case, since handling procedures were identical at both sites, it is likely that any mortality would have affected the results equally at both sites.

A third assumption is that crab catch during the first day of a sample (i.e., when the northern half of each site was sampled) did not affect crab CPUE during the second day, when the southern half was sampled. We do not know how far crabs move in order to feed, but it is likely that at least some crabs moved from one half of the plot to the other half during the two days of each sample period. We also do not know if crabs become "trap-shy" or, conversely, if they become dependent on pots for food. Such behavior would be of concern if we were attempting to estimate absolute abundance or density of crabs, but is of lesser concern in this experiment, which estimates CPUE. It is likely that such behavior, if it affected the experimental results at all, would have affected both sites equally.

The results of this test revealed a high level of natural variability in crab CPUE. Possible reasons include the migratory nature of crabs, which move onshore and offshore in response to molting and reproductive cues. Other possible factors include cyclic abundance patterns and behavioral changes related to food availability. Commercial catch rates of Dungeness crabs in Washington, Oregon, and California have historically been highly unstable, and have been correlated with a number of abiotic and biotic factors (Methot 1989). In addition, crab CPUE in our experiment could have been affected by recreational crabbing which occurred at both sites. During WDFW sport crab surveys, crab pots were observed at the treatment site in August and October 1991, and at the control site in October and November 1993, as well as in February and March 1994. This recreational crabbing may have been partly responsible for the apparent decline in estimated CPUE at the control site between samples 16 and 17, a period during which estimated CPUE at the treatment site increased.

This high natural variability in crab CPUE reduced the statistical power of the experiment. Although we detected no significant change in crab CPUE following geoduck fishing at the treatment site, power analysis revealed that CPUE would have to increase or decrease roughly 176% before we would have a 90% chance of detecting the change. We sampled the site 20 times during 4.6 years with 30 crab pots on each occasion, so from a practical sampling standpoint, this low level of statistical power is probably unavoidable. We can expect that such natural variability in crab CPUE would also affect recreational crabbers, and probably to a much greater degree since they are limited in the number of "samples" they can take. Therefore, anecdotal reports which allege that commercial geoduck fishing drastically reduces crab catches cannot be given much credence.

ACKNOWLEDGEMENTS

We thank Tom Cain, L. Goodwin, D. Herren, B. McLaughlin, J. Odell, P. Roni, D. Rothaus, B. Sizemore, L. Timme, and B. Wood for many days of help baiting, setting, and retrieving crab pots. A. Hoffmann and J. Tagart provided biometric guidance and helpful reviews of an early draft.

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Table 1. Results of Dungeness crab sampling at the control and treatment sites in Hood Canal. "Pre-fishing" refers to sample numbers 1-10, "post-fishing" refers to sample numbers 11-20. Legal crab refers to males > 151 mm carapace width.

			CONTROL					TREATMENT				
			CATCH		EFFORT	CPUE (NUMBER CRABS/POT)		CATCH		EFFORT	CPUE (NUMBER CRABS/POT)	
sample	date	time (days)	TOTAL CRAB	LEGAL CRAB	NUMBER OF POTS	TOTAL CRAB	LEGAL CRAB	TOTAL CRAB	LEGAL CRAB	NUMBER OF POTS	TOTAL CRAB	LEGAL CRAB
1	12/12/90	0	44	26	24	1.83	1.08	17	8	24	0.71	0.33
2	03/15/91	93	148	121	24	6.17	5.04	62	49	24	2.58	2.04
3	04/19/91	128	153	116	24	6.38	4.83	69	57	24	2.88	2.38
4	07/03/91	203	257	185	30	8.57	6.17	113	74	30	3.77	2.47
5	08/22/91	253	74	20	30	2.47	0.67	22	12	30	0.73	0.40
6	10/17/91	309	188	93	30	6.27	3.10	36	18	30	1.20	0.60
7	12/13/91	366	106	64	30	3.53	2.13	20	17	30	0.67	0.57
8	02/28/92	443	157	113	30	5.23	3.77	92	75	30	3.07	2.50
9	06/11/92	547	160	117	30	5.33	3.90	33	29	30	1.10	0.97
10	07/30/92	596	58	34	27	2.15	1.26	9	3	30	0.30	0.10
11	09/27/92	655	63	40	15	4.20	2.67	9	4	15	0.60	0.27
12	11/15/92	704	148	108	30	4.93	3.60	31	21	29	1.07	0.72
13	12/13/92	732	114	90	30	3.80	3.00	46	38	30	1.53	1.27
14	02/25/93	806	202	140	30	6.73	4.67	138	121	30	4.60	4.03
15	05/07/93	877	176	111	30	5.87	3.70	77	68	30	2.57	2.27
16	06/26/93	927	263	195	30	8.77	6.50	51	43	30	1.70	1.43
17	06/19/94	1285	162	130	30	5.40	4.33	281	191	30	9.37	6.37
18	02/28/95	1539	124	98	30	4.13	3.27	143	120	30	4.77	4.00
19	05/03/95	1603	65	51	30	2.17	1.70	45	37	30	1.50	1.23
20	07/12/95	1673	75	56	30	2.50	1.87	56	46	30	1.87	1.53
MEAN (PRE-FISHING)			134.50	88.90		4.79	3.20	47.30	34.20		1.70	1.24
MEAN (POST-FISHING)			139.20	101.90		4.85	3.53	87.70	68.90		2.98	2.31

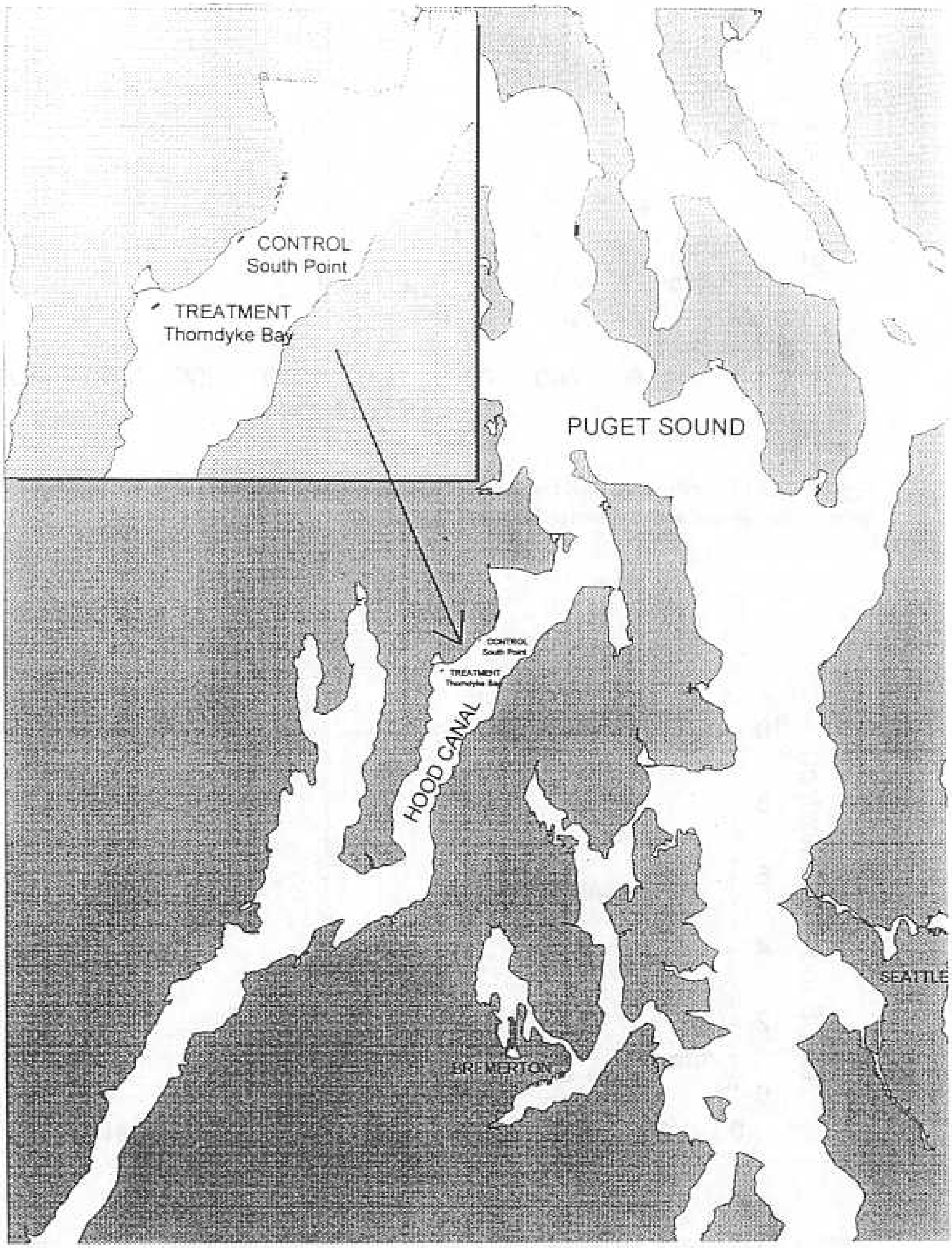

Figure 1. Location of the control and treatment sites in northern Hood Canal which were sampled for Dungeness crab catch per unit effort.

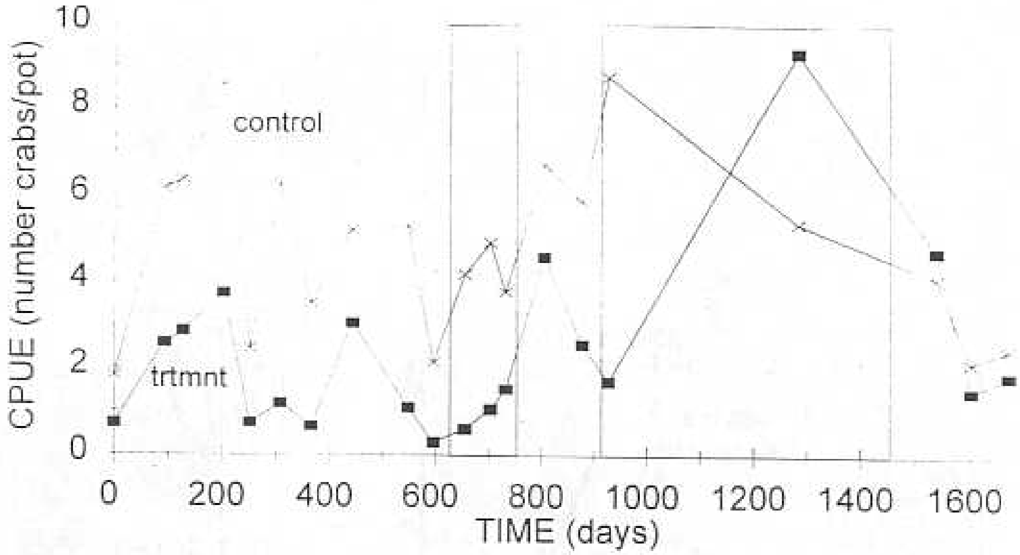

Figure 2. CPUE (crabs/pot) of all Dungeness crabs at the control and treatment sites. Shaded areas indicate the two periods of commercial geoduck fishing.

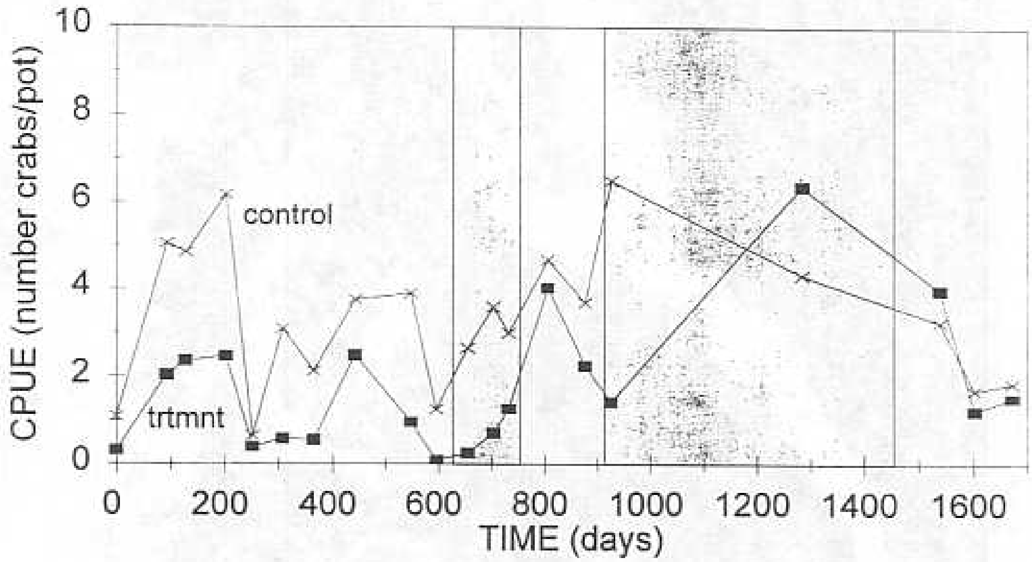

Figure 3. CPUE (crabs/pot) of legal Dungeness crabs at the control and treatment sites. Shaded areas indicate the two periods of commercial geoduck fishing. Legal crabs are males > 151 mm carapace width.

Appendix 8

HOOD CANAL REGION

HARVEST MANAGEMENT PLAN FOR THE SUB-TIDAL GEODUCK (*Panopea abrupta*) FISHERY

1. Parties To This Plan

The following are parties to this Agreement: the Washington Department of Fish and Wildlife, the Washington Department of Natural Resources, the Jamestown S'Klallam, Port Gamble S'Klallam, Lower Elwha S'Klallam, Skokomish and Suquamish Tribes

2. Region Covered By This Plan

This Harvest Agreement encompasses the sub-tidal lands of Hood Canal described as those waters south of a line projected from Olele Point to Foulweather bluff including the area described as Dabob Bay (figure 1)

3. Term Of This Plan

This Plan supercedes provisions in all previous geoduck harvest management agreements between the state and Treaty Tribes for the Hood Canal Geoduck Management Region. The term of this Plan is from April 1, 2001 to March 31, 2002. This Plan may be terminated by any party by giving thirty (30) days written notice to all parties to this Plan. This Plan is limited to the time and matters expressly stated herein.

4. Purpose Of This Plan

This Harvest Management Plan is intended to be consistent with paragraph 4.5 of United States v. Washington, Case No. 9213, subproceeding 89-3 (hereafter "Implementation Order"). The purpose of this Plan is to establish guidelines and general provisions governing management and harvest of geoduck clams (*Panopea abrupta*) in the Hood Canal Management Region (region described above in section 2). The parties agree to a philosophy of cooperative management in developing and implementing sub-tidal geoduck fisheries. The objectives of this Plan are to provide sustainable harvest of geoduck resources consistent with the best available scientific information, protect public health, protect habitat required to sustain geoducks, minimize the impact of harvest on the ecosystem, provide a controlled and orderly fishery, achieve the allocation objectives established in the Implementation Order, and provide a compliance and enforcement program to achieve these objectives.

This Plan is intended to ensure that Treaty Indian and state fishers, subject to their respective regulatory authorities, shall be accorded the opportunity to harvest their shares of geoduck clams as determined by the court in this case, provided that express provisions of this Plan shall control over general provisions of applicable court orders.

This Plan shall not affect nor be considered by any person, party, or court to affect the continuing jurisdiction of the United States District Court for the Western District over all issues and matters within the jurisdiction of that court pursuant to the rulings in *United States v. Washington*, Case No. 9213, sub-proceeding 89-3 (W.D.Wa.). The parties agree they remain bound by § 1.6 of the Implementation Order, continuing the implementation of the Shellfish Sanitation Consent Decree (May 4, 1994).

By entering into this Plan, no party waives any rights under the orders of the court in this matter, except as expressly stated herein.

5. No Waiver Or Admission Of Usual And Accustomed Areas

No party hereto waives any claims concerning the location, boundaries, scope, or use of usual and accustomed grounds and stations. This Plan does not constitute an admission that a particular area used for management is an accurate description of usual and accustomed grounds and stations, their location, boundaries, scope or use. The terms of this Plan shall not be used as evidence in any Tribal, State, or Federal Court of administrative or quasi judicial proceeding concerning the location, boundaries, scope or use of usual and accustomed grounds and stations.

6. Equal Opportunity Shall Govern Harvest

The State and Tribal harvest opportunity shall be equal and acceptable in terms of geoduck quality, value, ease of digging, density, access, and interference or interruption from other uses. The parties acknowledge that principles of equal opportunity may require evaluation of intangible factors, including the ability to obtain the benefit of first access to unharvested areas and preserving equal harvesting opportunities in the future. Where appropriate, individual tracts that are designated for harvest may be divided to preserve present and future harvesting opportunities. The parties recognize the need to maintain complete and valid resource surveys in order to provide future harvest opportunities. The parties recognize that both the state and treaty tribes have an equal responsibility to conduct resource surveys (according to WDFW Technical Report #FPT00-01, "Stock Assessment of Sub-tidal Geoduck Clams, *Panopea abrupta*, in Washington", unless otherwise agreed by all parties).

7. Accommodation Of Multiple Tribal Usual and Accustomed Fishing Areas Within the Region and Constraints Faced By The State

The parties recognize that individual Tribes may be restricted in their access to a portion of the geoduck resource within the region due to geographic limitations of their Usual and Accustomed Fishing Areas. The parties also recognize that the state's access to geoduck resources within the region is affected by various factors, including statewide management planning and local government permitting processes. The parties shall harvest geoducks such that the harvest will not disproportionately concentrate impact in any one portion of the region or otherwise cause substantial impact to another party's rights. The geoduck resource is unevenly distributed throughout each region, which may affect proportional harvest. The intent of the parties to harvest a tract to at least 65% of the pre-harvest biomass before moving to a new tract may also affect the goal of proportional harvest.

8. Risk Of Rights By Other Tribes

If a Treaty Tribe not party to this Plan has rights to harvest in this region, then any amount actually taken by that Tribe in this region shall count against the Tribal share.

9. Notice of Harvesting and Harvest Regulations

The State and Treaty Tribes shall regulate their respective geoduck fisheries to comply with all provisions of this Plan. State geoduck fishing will be conducted under WDFW regulations including RCW 75.24.100, WAC 220-52-019, WAC 220-52-01901, and WAC 220-20-026; provisions in the Puget Sound Commercial Geoduck Fishery Management Plan and Environmental Impact Statement (1985 or the most recent version available); and sales of valuable materials contracts issued by the DNR. Specific openings and closures for Tribal geoduck fisheries shall occur by Tribal regulation, or notice of harvest pursuant to regulations.

All commercial and subsistence harvests, whether by Tribal regulation or state sale, shall be preceded by written notice to the persons designated below or as otherwise agreed. Notice shall be delivered by mail, facsimile or other agreed to electronic communications at least 3 working days prior to a harvest pursuant to this Plan. All notices shall include at a minimum the following provisions:

* Fishery type
* Harvest date and hours
* Gear type
* Catch reporting requirements
* Specific harvest site
* Designated off-load site
* Harvest limits
* Expected harvest effort

The following persons are designated to receive notices and regulations. In addition, the parties agree to distribute the names of Tribal and State harvest monitors to any party to this agreement, along with the monitor's cell phone number, upon request.

Contacts	Organization	Fax Number
Tamara Gage	Port Gamble S'Klallam Tribe	360 297-4791
Scott Chitwood	Jamestown S'Klallam Tribe	360 681-4611
Pat Crain	Lower Elwha S'Klallam Tribe	360 452-4848
Dave Herrera	Skokomish Tribe	360 877-5148
Randy Hatch	Point No Point Treaty Council	360 297-3413
Paul Williams	Suquamish Tribe	360 598-4666
Bob Sizemore	Department of Fish and Wildlife	360 9022943
Dave Palazzi	Department of Natural Resources	360 902-1786
Stan Iwagoshi	Department of Health	360 236-2257

10. Enforcement

Each party shall adopt, prior to any harvest, regulations that carry into effect this Plan. Conditions of such Tribal and State harvest regulations, or DNR harvest contracts, will be enforced according to the authority of the respective party. All aspects of harvest shall be subject to enforcement, including off-tract harvest. Enforcement programs will include, at a minimum, establishment and maintenance of tract boundaries, on-site and under water monitoring during harvest operations, and harvest accounting. Each party will ensure that all geoduck clam harvesting activity occurs only within tracts listed in this management plan and opened by valid regulation (or notice of harvest, if applicable). Any person who delivers, or knowingly allows delivery of geoducks taken from tracts not opened under provisions of this Plan or other State/Tribal Plan shall be subject to the respective party's regulatory actions and authority.

Primary enforcement vessels shall be equipped at all times with a properly functioning GPS unit and a fathometer.

If one party has information that another party is violating the terms of this Plan, it shall immediately notify the appropriate party(ies)in the Hood Canal Region. Notice of the alleged violation shall consist of a verbal and written report to the appropriate party(ies) and the violating party. The party allegedly violating the terms of the Plan shall then take meaningful steps to investigate the alleged violation and assure that the violation is rectified and that harvest comes into compliance. Any divers or contractors found guilty of violations shall be subject to the enforcement penalties of their respective party. The State and affected Treaty Tribes shall meet at least once per occurrence to resolve violation disputes. Disputes that cannot be resolved in this manner will be referred to formal dispute resolution (Section26).

11. Harvest Shall Occur Where Adequate Survey Data Exists

In order for a geoduck tract to be harvested, the area shall first be surveyed to determine the geoduck biomass available on the tract. Only tracts that have current (within 8 years) surveys can be opened for initial harvest, unless otherwise agreed. All affected parties shall be notified if surveys are to be conducted in the region. All dive surveys specified in this Plan will be conducted according to the methodology described in WDFW Technical Report #FPT00-01 unless otherwise agreed.

12. Recovery Study

Throughout Puget Sound specific geoduck beds, which have been fished down, are included in a long-term recovery study. The purpose of this study is to empirically verify changes in geoduck density (recovery) following fishing events. A series of post-fishing surveys are conducted to determine rates of recovery. Once the mean pre-fishing density is reached on a given bed, based on jointly agreed-to criteria (Section 13), the bed will be eligible for commercial harvest. Geoduck tracts that are included in the recovery study will not be harvested by any party to this Plan during this management period. For the Hood Canal Geoduck Management Region, Anderson Cove geoduck tract #22550 (2001 Geoduck Atlas) is included in the recovery study.

13. Tracts Will Be Fished Down and Managed for Recovery

The parties agree to a harvest management strategy that minimizes the number of tracts open in any one year in the region. This strategy provides for optimal survival and recruitment of geoducks on unfished tracts. Harvesting an unlimited number of tracts in the region in any one year, or harvesting the same tract for many years, could negatively impact the geoduck resource. In order to minimize the number of new tracts open each year in the region the parties agree to the following process:

Once a tract or a portion of a tract (described to all parties prior to fishing) is opened for fishing, the area will be harvested on a continuous basis until the parties agree the area has been adequately fished down. The minimum fished down level will be defined as either a percentage of the original biomass, or a density estimate that must be achieved prior to closing the tract. These quantities will be calculated by subtracting the amount harvested from the pre-fishing biomass estimate. The minimum fished down level will initially be set at 65% of the original biomass, or 0.04 geoduck/ft^2, and will be subject to annual adjustment by agreement of the parties. When the area has been fished out, that area will be described to all parties and placed in recovery status (even though the bed may not be formally in the recovery study). Tracts placed in recovery status may not be fished again until the pre-fishing and subsequent survey densities are not statistically different at the 95% confidence level using an appropriate *t*-test.

14. Harvests In Less Than -18 ft. MLLW And Greater Than -70 ft.

The parties reserve the right to harvest in areas less than -18 ft. corrected to mean lower low water (MLLW) and greater than -70 ft. uncorrected depth. These areas must be surveyed and opened to harvest based upon biologically appropriate criteria. Harvest shall be conducted so as to limit the impact to the geoduck resource and protect eelgrass beds and other critical habitat and resources.

15. National Shellfish Sanitation Program (NSSP) Compliance

Geoducks shall only be commercially harvested in tracts certified by the Washington Department of Health in accordance with the Shellfish Sanitation Consent Decree in *United States v. Washington,* Case No. 9213, sub-proceeding 89-3 (W.D.Wa., May 4, 1994).

16. Harvest Areas Shall Be Marked

An area shall not be open at any time for harvest unless the boundaries are accurately described and marked. An area opened for harvesting shall be set apart and marked at all times, with easily identifiable stakes and buoys, by the party regulating the harvest. The area shall be marked sufficiently to assure compliance with this Plan, and to allow meaningful compliance with all regulations of the party opening the area for harvest. The shallow water and deep water corners of the tract should be marked with buoys of the same color, and the shoreward boundary of the tract should be marked with buoys of a different color. If marking the shoreward boundary is impractical, the parties may agree on an alternate marking and/or enforcement strategy, on a case-by-case basis, to prevent harvest in shallow areas. The latitude and longitude positions and corrected water depths of each buoy marker set on a tract must be provided to all parties, upon request. Positions will be recorded using GPS, dGPS, or equivalent, and North American Datum 1927 data set (which relates to NOAA navigation charts). For harvest areas of 100 acres or less, the near shore marking buoys delineating the shoreward tract boundary should be set apart no more than 500 feet. For tracts over 100 acres, the near shore marking buoys delineating the shoreward tract boundary should be set apart no more than 800 feet. Tracts with highly variable depth contours may require more than the minimum marking to adequately characterize the harvest area. Tracts in confined waterways or tracts with steeply sloping geography may require different marking, which must be agreed to by all parties. Any missing, moved or misplaced buoys will be marked at least temporarily on any given fishing day and replaced permanently within 5 harvest days unless otherwise agreed by all parties.

No harvest shall occur in eelgrass beds or eelgrass buffer zones. Eelgrass beds and necessary buffering areas shall be determined, marked, and excluded from the designated harvest area prior to harvest. The shoreward boundary of the tract is the -18 feet mean lower low water (MLLW) depth contour or deeper. The seaward boundary is at -70 feet uncorrected depth. On tracts where an eelgrass bed extends deeper than -16 feet (MLLW) the shoreward boundary of the tract will be two vertical feet deeper and seaward of the deepest occurrence of eelgrass. Alternatively, a buffer zone of at least 180 feet around eelgrass beds deeper than -18 feet (MLLW) can be used when the tract is marked to exclude eelgrass and marking is visible under water to divers within the tract.

17. Harvest Gear And Methods

Commercial geoduck harvest shall be conducted by divers with a hand-held, manually operated water jet. The water jet nozzle shall not exceed 5/8 inch inside diameter. Use of other gear may occur upon written agreement between the parties to this Plan. Each geoduck must be excavated individually from the substrate. The practice of excavating geoducks from the side or "side-mining" is prohibited on all tracts.

18. No Over-harvest

The parties shall harvest in accordance with their respective state/tribal shares in the Hood Canal Region. The parties agree to close their respective fisheries by the time that their share of the TAC, as specified in Section20, has been reached. Any over-harvest disputes will be resolved in a timely manner. Those that cannot be resolved by informal meetings between the parties will be referred to formal dispute resolution (Section26). Over-harvest of respective shares, by any party, without agreement between the parties, will result in adjustment of the violating party's share the following year, thus paying the over-harvest back to the resource. There shall be no claim, harvest offset, or defense to harvest based on foregone opportunity.

19. A Calculated Sustainable Yield Shall Dictate Harvest Amount

The parties agree to conduct geoduck harvest based on the assumption that the Hood Canal Region can sustain a calculated sustainable yield each year in accordance with the procedures described in WDFW Technical Report #FPT00-01, "Stock Assessment of Sub-tidal Geoduck Clams, *Panopea abrupta,* in Washington". The method for determining the sustainable harvest rate may be changed if the parties agree that such changes are warranted. The parties shall cooperatively determine the appropriate values for model parameters and the fishery exploitation rate in order to calculate the regional sustainable yield.

The affected parties will review the status of commercial geoduck tracts surveyed prior to 1981, and make adjustments where necessary to change the show factor to 0.75 in order to estimate the tract biomass (except where a site-specific show plot is available). For tracts with less than 0.1 transects per acre, the parties will review the confidence interval associated with that survey data, and jointly determine if additional survey work is needed to obtain more reliable biomass estimates.

Each year, prior to harvest, the parties will discuss and determine the status of each tract, or portions of tracts, to be opened for fishing in the Hood Canal Region. The parties agree to cooperatively update the Geoduck Atlas to include all new data on beds that are newly-discovered, re-surveyed, harvested, polluted, or the status of which has changed. An objective is to distribute a working draft of the annual Geoduck Atlas to all parties by February 1, allow a one month review/comment period, and finalize the Atlas by March 1 each year. All harvests and geoduck survey information through December 31 will be exchanged by each party by January 15. All harvests including commercial harvest, commercial take-home, resource assessment dig samples, brood stock collection, research, and PSP samples must be reported and will be attributed to respective parties shares, unless otherwise agreed.

20. Harvest Quotas

The 2001-2002 fishery season quotas include all fishery related mortalities and are based on an annual harvest rate of 2.7% of the total commercial biomass in the Hood Canal region. The 2.7 % harvest rate was recommended using the age based equilibrium yield described in WDFW Technical Report #FPT00-01. Currently, the best available geoduck population data indicates the harvestable commercial biomass in the Hood Canal Region is 40,062,000 pounds (see Appendix A). The Tribal and State harvest quota for the April 1, 2001 to March 31, 2002 fishery season in the Hood Canal Region is 540,837 pounds each. These harvest quotas for the Tribes and for the State will be taken from the respective list of tracts identified in Section 21, unless otherwise agreed. If either party does not harvest its share during the planned harvest year, the unharvested allocations will not be carried over to the following year.

21. Harvest Areas

The specific Tribal and State harvest areas are listed below with their associated tract number, as designated in the 2001 WDFW Geoduck Atlas. The associated tract maps and boundary descriptions are attached in Appendix B.

Tribal Sites:

Port Gamble	#20000
Port Gamble	#20100
Hazel Pt. (Toandos)	#21000
Warrenville (Big Beef)	#21450

State Sites:

Sisters/Shine East	#20300
Hood Head East	#20200
Hood Head South	#20250

Alternative sites may be added to this Plan for both the Tribal and the state fisheries if the tracts identified in the above lists are not available for harvest. No additional sites shall be selected for harvest other than those listed above except by written agreement amongst the Treaty Tribes, WDFW, and DNR.

22. Protection of Fin Fish Spawning Sites

Finfish, and particularly herring, spawning populations could be negatively impacted by geoduck harvesting. In order to protect finfish populations, the parties agree to restrict geoduck harvesting in areas of known spawning activity. The following tables identify management actions for both Tribal and State geoduck harvest sites that would be implemented during the 2001 season to protect herring spawning populations:

Tribal Sites:

Geoduck Tract	Management Action: February 15 thru March 31
Port Gamble #20000	Closed to harvest, or harvest restricted to 35 feet or deeper
Port Gamble #20100	Closed to harvest, or harvest restricted to 35 feet or deeper

State Sites:

Geoduck Tract	Management Action: February 15 thru March 31
Sister/Shine East #20300	Closed to harvest, or harvest restricted to 35 feet or deeper

The Tribes and the state may mutually agree to adjust the above closure periods if herring stock information suggests a different management action is necessary to protect the herring spawning population. The parties also agree to continue discussions on the implementation of management measures that may be taken to provide additional protection to herring spawning substrates. Any agreed-to management restrictions to provide further substrate protection will be appended to and become a part of this Plan.

23. Harvest Monitoring And Catch Accounting Procedures

The Tribes and the State shall manage their respective fisheries in such a manner that prohibits over-harvest, high-grading, and inaccurate reporting of the total catch. For purposes of this Plan, "high-grading" shall be defined as the practice of discarding or dumping geoducks at any time, resulting in excavated clams not being weighed, reported, or accounted for. The parties shall require that all geoducks that are excavated from the substrate during a harvest event shall be retained and reported as pounds of harvested geoducks. Such harvest shall be counted against that party's share, unless otherwise agreed to in writing. All commercial sales and commercial take home harvest must be reported on fish receiving tickets at the weigh out site or point of sale. Any subsistence or ceremonial harvest will be accounted for by reporting the harvest on an appropriate record keeping form, as determined by the harvesting party.

All parties shall share harvest and landing reports with all other parties on a monthly basis. Monthly distribution of harvest data will occur by the 15th of each month, and will include harvest for the period from the opening of the current season's fishery through the end of the previous month. The Point No Point Treaty Council will be responsible for collating harvest data from all tribes in the Hood Canal Region for distribution to all affected parties. Likewise, DNR will be responsible for summary and distribution of state geoduck harvest in Hood Canal to all affected parties.

The parties recognize that there are potential sources of geoduck mortality caused by fishing activity that are not consistently reported, including inadvertent harvest loss, intentional discarding, and unreported catch. The parties agree that fishery management programs will include estimates of these potential mortality sources in total harvest estimates, while minimizing the incidence of unreported mortality through the implementation of adequate fishery monitoring and compliance programs. The parties also recognize that the actual elements of such harvest adjustments or monitoring programs will vary with the type of fishery conducted.

In the Hood Canal Region, the parties agree to account for unreported mortalities by including a harvest loss estimate in their total reported harvest. The parties further agree to minimize unreported mortality through the use of the following specific harvesting monitoring and compliance procedures:

1) All geoduck fishing shall occur with a monitor, either on site or within visual distance of the tract at all times, except during operational or emergency requirements, who will not participate in the fishery or share the harvest. The duties and responsibilities of the monitor shall include accurate accounting and reporting of all geoducks harvested during fishing operations. The monitoring vessel and/or harvest vessels shall carry a calibrated scale available for weighing geoducks and geoduck cages, which will be verified for accuracy prior to each weigh out. Primary monitoring vessels shall be equipped at all times with a properly functioning GPS unit and a fathometer.

   Compliance dives or visual observations of the tract seafloor shall occur periodically by enforcement divers or monitor personnel (who are not participants of the fishery) such that one observation period will occur for every 5 days that fishing proceeds on the tract, provided that observations may proceed on a more frequent schedule when deemed necessary.

   All parties agree to complete daily monitor logs of harvest and monitoring activities. Appendix C of this management plan provides information that could be included in harvest monitor logs.

2) All harvested geoduck shall be weighed by the monitor aboard the harvest vessel, on the water, at the harvest site, and within the tract boundaries, provided that the parties may elect to waive the on-the-water weigh out requirement for tract #20000 and tract #20100 due to the close proximity of these tracts to the offload site. If on-the-water weigh out is waived for these tracts, the parties harvesting these tracts agree to conduct a harvest inventory aboard each harvest vessel, as stipulated below.

3) If exigent circumstances exist (such as high wind or waves at the harvest site), which precludes weighing of geoducks on the harvest vessel, or if geoducks are harvested from tract # 20000 or tract #20100, then geoducks may be weighed at a previously designated offload site. If geoducks are to be weighed at a previously designated off-load site, the monitor shall attempt to inventory the harvest aboard each vessel prior to departure from the harvest tract, subject to reasonable safety requirements based on prevailing conditions. The inventory should include a written record of the number of fully loaded and partially loaded standard crates. At the discretion of the monitor, the inventory may also include: 1) an estimate of the percent loaded in partially loaded crates, and 2) a thorough inspection of each vessel to detect harvested geoducks. Each inventory report shall be made available to parties to this Plan, upon request.

4) The monitor shall take measures necessary to observe and report any discarding of geoducks between the harvest site and the landing site. The monitor or on-site enforcement officer will take all reasonable measures to assure that the harvest area is accurately marked and that harvest does not occur outside of the tract boundaries. In addition, all harvesters must notify the monitor prior to leaving the tract or crossing a tract boundary. In such cases, the monitor will either inventory the vessel's harvest as stipulated above, or the harvest will be weighed and recorded before the vessel is allowed to proceed.

5) Weighing of geoducks shall be witnessed by an authorized Tribal or state official of their respective fishery. Any party to this Plan may observe any other party's harvest and compliance activities, with prior notification.

24. Post-Harvest Surveys

The parties have identified the following tracts in the Hood Canal Region that are eligible for post-harvest surveys: Tala Point/Colvos Rock and Tala Point South. Eligibility criteria includes a tract that has been closed to fishing. Post-harvest surveys will be used to update the Geoduck Atlas biomass following completion of the surveys. The parties will agree to additional uses of post-harvest survey data as appropriate. The parties to the Hood Canal Region will determine the method of analysis for comparing pre-harvest biomass estimates with post-harvest biomass estimates plus reported catch, and when appropriate, the timeframe and distribution for payback when significant differences in the estimates indicate non-reporting has occurred.

Post-harvest surveys should be conducted within two years of closing a tract. The party(ies) harvesting a particular tract should be responsible for the post-harvest surveys on that tract. However, the parties are free to negotiate alternate survey responsibilities within the Hood Canal Region. Post-harvest survey methods are described in Appendix D.

25. Unregulated Harvest (Poaching)

Within Hood Canal, if the source and quantity of geoduck taken by poaching on a commercial tract is known, that amount will be deducted from the tract biomass. When poaching results in over-harvest, as agreed to by the parties, the parties will meet to discuss management actions needed to ensure the TAC is not exceeded, according to a schedule and method as agreed to by the parties.

26. Dispute Resolution

Before initiating formal dispute resolution the parties shall first attempt informal resolution of any disputes regarding provisions of this Plan. The process of informal resolution shall include written notice that fully describes the dispute and at least one meeting (in person or telephonic) concerning the dispute. If such a process does not resolve the dispute, the parties agree to consider the following formal dispute resolution process for the purpose of this plan: The parties will create a panel of three persons with expertise or experience in the geoduck fishery, where the state chooses one person, the tribe(s) choose the second, and those two persons choose a third person. The parties will present their dispute to that panel. The panel may review the dispute, but its obligation is to issue a written decision that implements the letter of this Plan by requiring appropriate action by the party or parties who are not in compliance. The Panel shall consider only those disputes that relate to management or technical issues. The parties shall retain the right to submit any legal disputes to the U.S. District Court for Western Washington with continuing jurisdiction in *U.S. v Washington*, Case 9213, sub-proceeding 89-3. The Panel shall have no powers beyond implementing this Plan. The Panel's decision shall not be precedential beyond the term of this Plan, and each party reserves the right to negotiate for a future Plan that would be contrary to the decision of such a Panel.

27. Changes To This Plan

Changes to this Plan may be made only upon written agreement by all signatory parties.

28. Authorized Signatures

This Plan is made by the following parties, and each of the undersigned persons has authority to enter this Plan under the federal court's Implementation Order.

For the Lower Elwha Klallam Tribe:

name:____________________________
date:______________________

For the Skokomish Tribe:

name:____________________________
date:______________________

For the Jamestown S'Klallam Tribe:

name:____________________________
date:______________________

For the WDFW:

name:____________________________
date:______________________

For the Port Gamble S'Klallam Tribe:

name:____________________________
date:______________________

For the WDNR:

name:____________________________
date:______________________

For the Suquamish Tribe:

name:____________________________
date:______________________

Appendix A

Commercial geoduck tracts used in calculating the 2001 fishery quotas for the Hood Canal Region

Tract No	Tract Name	Acres	Clams / Sq Ft	Pounds X 1000	Status
19200-350	Tala Pt. Colvos Rock	220	0.04	537	Closed, Need post harvest Survey
19400	Tala Pt. South	38	0.35	763	Closed, Need post harvest Survey
19450	Point Hannon	120	0.06	485	Currently being fished
19550	Foulweather Bluff	40	0.17	447	Inactive
19650	Foulweather	64	0.24	1016	Inactive
19700	Foulweather 1	39	0.1	272	Inactive
19750	Foulweather 2	19	0.43	769	Inactive
19900	Coon Bay	99	0.22	2570	Inactive
20000	Port Gamble Outside	264	0.56	9635	Currently being fished
20100	Port Gamble Bay	185	0.11	3408	Currently being fished
20200	Hood Head East	33	0.31	746	Currently being fished
20250	Hood Head South	40	0.27	862	Currently being fished
20300	Sisters/Shine	459	0.09	3798	Currently being fished
20400	Case Shoal	75	0.06	312	Inactive
20450	Case Shoal South	182	0.07	748	Currently being fished
20550	Thorndyke	147	0.11	1029	May need post harvest survey
20600	Hood Canal Bridge	46	0.42	1264	Inactive
20650	Bridge	43	0.26	645	Inactive
20700	Lofall	170	0.07	757	Currently being fished
20750	Vinland	100	0.19	1266	May need post harvest survey
20800	Brown Point	31	0.24	408	May need post harvest survey
20900	Brown Point South	20	0.08	86	May need post harvest survey
21000	Hazel Point	179	0.18	3266	Currently being fished
21150	Bangor/Trident	116	0.09	651	Inactive
21350	Olympic View	20	0.26	433	Inactive
21450	Big Beef	421	0.09	2917	Currently being fished
21750	Broadspit	24	0.04	86	Inactive
22350	Stavis Bay	6	0.05	28	Inactive
22450	Tekiu Point	13	0.04	59	Inactive
22550	Anderson Cove	65	0.02	117	In recovery study
22650	Quatsap Point	20	0.05	85	Inactive
22850	Hamma Hamma	14	0.03	39	Inactive
23100	Lillwaup	58	0.04	190	Inactive
24000	Sisters Point	62	0.07	368	Inactive
Total: 40,062,000 pounds Harvestable amount: (2.7%) * (40,062,000) = 1,081,674 pounds					

Appendix B

Geoduck tract maps and tract boundary descriptions for the Hood Canal Region

ATTACHED

Appendix C

While additional work is needed to develop a specific form and data elements for monitor logs, the following information currently collected by state monitors is provided as a recommendation:

1. Name of harvest monitor responsible for completing compliance log
2. Time and date harvest monitor arrives at harvest site
3. Time and date harvest monitor leaves harvest site
4. Time and date each harvest vessel enters the harvest site
5. Time and date each harvest vessel leaves the harvest site
6. Time, date, vessel name or number, name of vessel operator, and names of divers on each harvest vessel.
7. Time, date, and vessel name of each vessel for each compliance check; findings of each compliance check; and any enforcement actions taken
8. Time and date of under water compliance checks, name of harvester, and name or number of vessel checked

Appendix D
POST-HARVEST SURVEY PROCEDURES

Post-harvest surveys will be conducted in the same manner as pre-harvest surveys (per "Stock Assessment of Subtidal Geoduck Clams *(Panopea abrupta)* in Washington" *WDFW Technical Report No. FPT00-01*), with the following exceptions or modifications:

1) Statistical Precision: The 95% confidence bound on the estimate of post-harvest biomass will ***not*** be required to lie within ±30% of the biomass estimate itself (as is required of pre-fishing survey estimates).

2) Sample Size and Placement of Transects: The layout of systematic grid lines of transects for post-harvest surveys will follow the procedures for pre-fishing surveys in *WDFW Technical Report No. FPT00-01* (in the section "Standard Layout of Systematic Grid Lines"). Briefly, this calls for the first grid line of transects to begin at a randomly-selected point along the tract's 18 ft MLLW contour, and subsequent lines of transects are placed at 1,000-ft intervals along the entire length of the tract's 18 ft MLLW contour. The only exception to this spacing would occur if the pre-fishing survey on the tract used a smaller interval, in which case the post-harvest survey will use the same interval. Following this procedure, it is expected that the sample size (i.e., the number of transects) for post-harvest surveys will be very similar to the sample size for the pre-fishing survey on the same tract. Some minor difference in sample size is expected, since the first grid line of transects for the post-harvest survey will begin at a different location along the inshore contour (due to random placement), and because there will inevitably be variations in the exact course swum by divers on the two surveys.

3) Dig Samples: Dig samples of geoducks need ***not*** be taken during post-harvest surveys except in the special case described below. In most cases, the biomass estimate for the post-harvest survey will be the product of the mean density of geoducks (from the ***post-harvest survey***) and the mean weight per geoduck (from the ***pre-fishing survey***). If, however, the post-harvest biomass estimate results in rejection of the null hypothesis (i.e., if the *t*-test suggests that statistically significant non-reporting has occurred on the tract), then a dig sample will be taken and the mean weight-per-geoduck estimate will be re-calculated using this post-harvest dig sample. The dig sample, if required, will be an unbiased series of cluster samples taken in accordance with *WDFW Technical Report No. FPT00-01*.

4) Articulated shells: During post-harvest surveys, all articulated geoduck shells found within the boundaries of survey transects may be counted, and the shell length measured to the nearest millimeter. The number and shell length of any articulated shells removed from a tract by compliance or enforcement staff will be recorded and provided to the appropriate state or tribal biologist.

Appendix 9

STATE OF WASHINGTON January 1996

Responses of Nesting Bald Eagles to the Harvest of Geoduck Clams

Washington Department of
FISH and WILDLIFE
Wildlife Management
Research Division

Use this citation when referencing this document:

Watson, J.W., D. Mundy, J.S. Begley, and D.J. Pierce. 1995. Responses of nesting bald eagles to the harvest of geoduck clams (*Panopea abrupta*). Final Report. Wash. Dept. Fish and Wildlife, Olympia. 23pp.

RESPONSES OF NESTING BALD EAGLES TO THE HARVEST OF GEODUCK CLAMS *(Panopea abrupta)*

JAMES W. WATSON, DAVID MUNDY, JAMES S. BEGLEY, AND D. JOHN PIERCE.
Washington Department of Fish and Wildlife, 600 Capitol Way N., Olympia, WA 98501

EXECUTIVE SUMMARY

The geoduck clam (*Panopea abrupta*) fishery is the largest clam fishery in Washington state. Harvest of geoduck clams takes place from anchored boats offshore from marine waters throughout Puget Sound. The bald eagle (*Haliaeetus leucocephalus*), presently a state and federally listed threatened species, nests along many of these shorelines and may forage within clam harvest tracts. Potential effects of clam harvest activities on foraging eagles are twofold: moving boats can flush foraging eagles, and anchored boats may passively displace eagles from foraging areas and reduce foraging success. Long-term effects of reduced foraging are unknown, but may include impaired productivity and survival. Effects of stationary boating activities on bald eagle foraging behavior have rarely been studied.

We investigated the responses of nesting bald eagles to the harvest of geoduck clams in Puget Sound, Washington, in 1993 and 1994. We assessed human activities, foraging behavior, and home ranges at 8 territories during 296 observational bouts for 1896 hours. Boating activities constituted the majority of human activities by frequency (69% of 1014 activities), and pedestrian activities were the most important activity by time (57% of 312,528 human activity minutes). Clam harvest boats were the most prevalent boat type, and accounted for 38% and 25% of all activities by frequency and time, respectively. Eagles flushed in response to only 4% of 890 potential disturbances and only 1 of 34 responses was a result of geoduck clam harvest. Fewer than expected flushes occurred in response to boats and more than expected in response to pedestrians ($P < 0.001$), based on the observed levels of these activities.

Eagle and human activity parameters were compared at two territories where clam harvest boats were present on weekdays (influence) and absent on weekends (controls). On harvest days, foraging attempts were reduced but not significantly so ($P = 0.060$), and eagles tended to forage evenly throughout the day. Spatially, eagles spent little total time and search-capture time, and relatively few perch and flight visits for both harvest and non-harvest days at < 400 m from harvest tracts. Foraging attempts were the only eagle behavior parameter that occurred significantly < 400 away, but the distribution of foraging attempts was not different between harvest and non-harvest days ($P = 0.118$).

Geoduck clam harvest, conducted at the intensity and periodicity we observed, is unlikely to result in long-term adverse impacts on eagle productivity, but may result in short-term changes in eagle behavior. Minimizing effects of clam harvest on localized eagle populations is important on Hood Canal or other areas that are experiencing chronic reproductive failure, and can best be accomplished by documenting foraging areas to avoid harvest overlap, and limiting harvest intensity by location and time. Specifically, limiting harvest intensity to 1-2 boats/harvest period on an eagle territory, and harvesting prior to 1000 h will reduce effects of harvest.

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INTRODUCTION

Most studies investigating the effects of human activities on nesting bald eagles (*Haliaeetus leucocephalus*) have assessed impacts of these activities within nest stands (Mathieson 1968, Grubb 1976, Anthony and Isaacs 1989, Grubb et al. 1991, Grubb et al. 1992). Such activities have the potential to disrupt incubation or brooding behavior and impact productivity (Fraser et al. 1985, Watson et al. 1994). Human activities can also affect bald eagle feeding behavior (Stalmaster 1987), although this has generally not been studied on foraging areas in eagle nesting territories (McGarigal et al. 1991). Disturbance of foraging bald eagles in winter can cause energy stress resulting in reduced fitness (Stalmaster 1987).

The first research that experimentally investigated the effects of stationary boating activities on foraging eagles within nesting territories found that eagles remained an average of 400 m distant from stationary boats, and reduced eagle foraging time and the number of foraging attempts (McGarigal et al. 1991). The study was conducted in the Columbia River Estuary, in northern Oregon and southern Washington, where eagles foraged primarily in sub-tidal or shallow water, and scavenging was quite important (Watson et al. 1991). No similar studies have investigated the presence of stationary boats, and the resulting passive displacement of eagles that forage along marine shorelines.

The geoduck clam (*Panopea abrupta*) fishery is the largest clam fishery on the Pacific Coast (Washington Department of Natural Resources [WDNR] and Washington Department of Fisheries [WDF] 1985). Harvest of geoduck clams is conducted by divers from anchored small craft (30-40 foot-long boats) in water that is either 6 m deep at mean low low-water, or 200 m from shore, whichever is the furthest distance from shore. State regulations require that clam harvest be conducted in water 6-23 m deep. Of 261 geoduck clam tracts identified for Washington state, 121 are potential sites for commercial operation (Geoduck Tract Atlas, WDNR). One-hundred twenty-two of 536 occupied bald eagle territories in the state in 1995 were < 1.6 km from these geoduck tracts (WDFW, Wildlife Resource Data Systems [WRDS], unpubl data). The nature of geoduck clam harvest and proximities of clam beds, create the potential for bald eagle foraging and foraging areas to be impacted by this fishery.

This research evaluates the temporal and spatial relationships between geoduck harvest operations and behavior of bald eagles on nesting territories in Puget Sound, Washington.

Acknowledgements.--Support for this research was provided by the Aquatic Lands Division of the WDNR, in cooperation with the Wildlife Research Division, WDFW. This report is fulfillment of contract # FY93-047. We thank K. McGarigal for statistical advice, S. Jennison for critical logistical support, C. Ringo and J. Talmadge for graphics assistance, and T. James for providing access and boat use at Naval Submarine Base Bangor. J. Almack, A. Bradbury, L. Goodwin, S. Jennison, and M. Schroeder reviewed earlier manuscripts. B. Cunningham and S. Ament assisted in data collection.

STUDY AREA

Eight bald eagle territories were selected for study in mid-Puget Sound (Fig. 1). Two territories (i.e. Squamish Harbor and Thorndyke Bay) were chosen based on the proposed harvest of associated clam beds in 1993 and 1994; the remaining territories were studied to document eagle use at future harvest locations. Primary foraging areas of all territories were in marine waters, and all nests were located < 300 m from the sound.

Sports fishing, commercial fishing, and recreational boating were common activities throughout the summer months on eagle foraging areas. Public shellfish harvest sites were found on many major beaches, and homesites were located along the shoreline.

Four of the eight eagle territories were located in Hood Canal. This local population of eagles, consisting of 35 nesting territories, has experienced depressed productivity for several years (WDFW, WRDS, unpubl. data). The possible association of chemical contaminants to impaired productivity for this population is currently being investigated (Watson et al. 1995, U.S. Fish and Wildlife Service, unpubl. data).

METHODS

Human and Eagle Activity Levels

We observed eagles at the eight territories between January and May to locate vantage points and identify foraging areas prior to geoduck harvest in June. We observed eagles at each territory for periods of six hours on a bi-monthly basis, and alternated starting times at 0600 and 1200 hrs. Time and duration of all activities of both adult eagles were recorded at distances < 2300 m from nests; when necessary, vantage points were selected that allowed better visibility of foraging activities associated with clam harvest beds, rather than activities at the nest. Small craft were used for observations at two territories that had limited upland vantage points (i.e. Tala Point and Hood Head). Perch locations and flight paths were recorded on 1:12,000 orthophotos. Weather information was recorded at the beginning and end of bouts, and we classified habitat types, predation attempts, perch zones, and human activity types (Appendix A). Timing and duration of human activities were recorded, as were the minimum distance of eagles to the activity, and from their nest. Duration variables were recorded in seconds, distance variables in meters.

We converted human activities, boating activities, and geoduck boat activities to activity minutes prior to analyses (HAMs, BAMs, and GAMs, respectively). One activity minute (e.g. 1 HAM) was equal to 1 activity conducted for 1 minute (McGarigal et al. 1991). Similarly, eagle activity times were converted to eagle-activity minutes (EAMs). Human and eagle activity parameters were both converted to a per-hour of observation basis to facilitate comparisons. Temporal relationships of eagle foraging were assessed with simple linear regression. We combined information from all territories to assess relationships of EAMs for total activity and search-capture time, and number of predation attempts, to Julian date. We

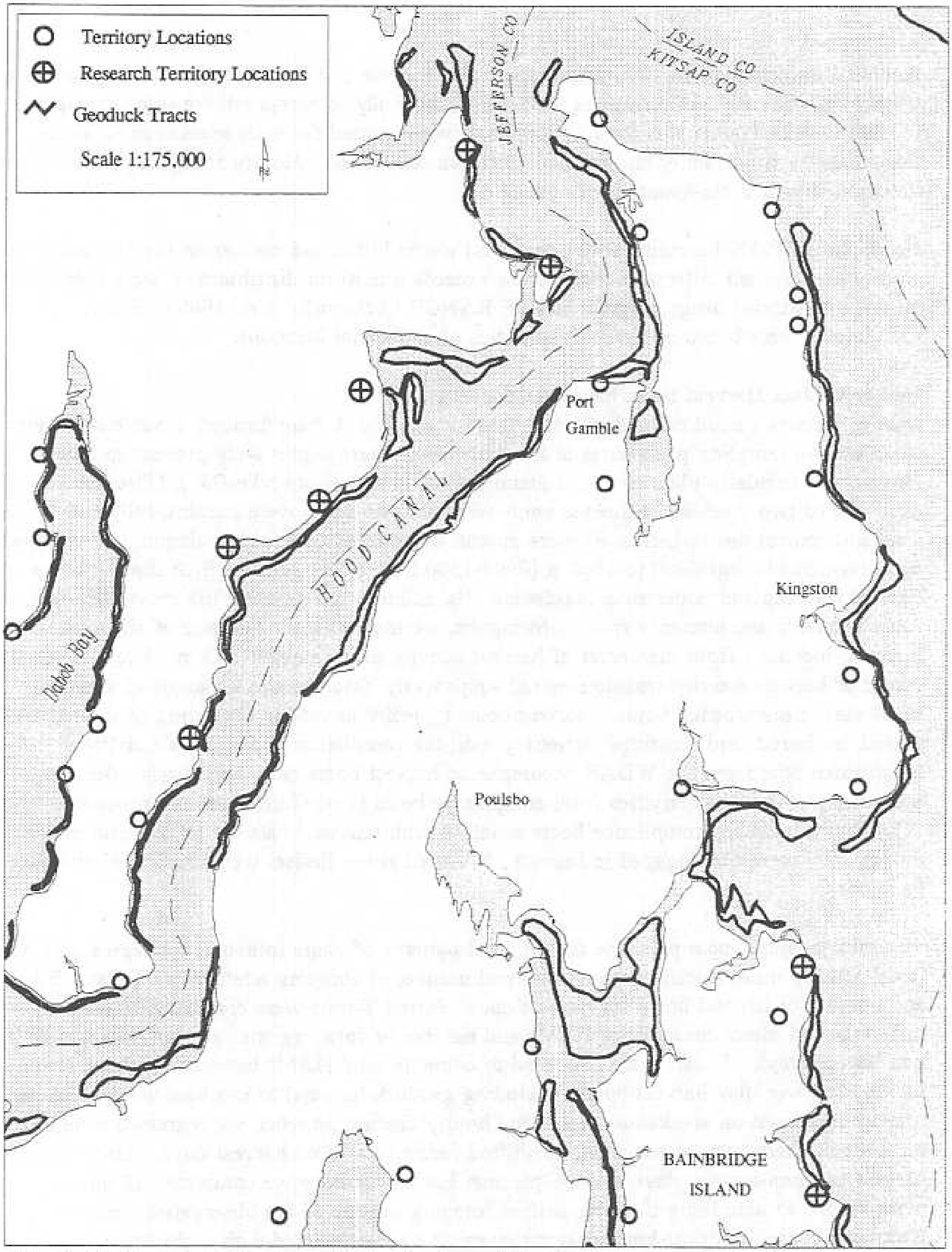

Fig. 1. Bald eagle territories and associated geoduck clam harvest tracts in mid-Puget Sound, Washington, where the effects of clam harvest on eagle behavior were studied in 1993 and 1994 (unpubl. data; Wash. Dept. Fish and Wild., Resource Data Systems; and Wash. Dept. Nat. Res., Aquatic Lands Division).

combined information for territories not involved in the geoduck disturbance study and the control days for the two territories involved in the study to assess relationships of eagle feeding to total HAMs and BAMs. Residuals were plotted for each regression to assess deviations from normality and the need for data conversion. Hourly foraging patterns were determined with a chi-square contingency test.

Home ranges (95% harmonic mean contours) were plotted and core areas (maximum areas where the observed utilization distribution exceeds a uniform distribution) were identified for all eagle territories using program HOME RANGE (Ackerman et al. 1989). Range calculations were based on perch frequencies of sequential locations.

Geoduck Clam Harvest Disturbance Assessment

During the nest period coincident with clam harvest (i.e. 1 June through 1 September) we modified the sampling procedures at two territories where eagles were present and clam harvest was regularly planned (i.e. Squamish Harbor and Thorndyke Bay). Observations consisted of two weekday influence bouts when harvest boats were present, followed by two weekend control days when boats were absent, as required by state regulation. Observations were conducted from 0900 to 1600 h (0900-1500 h in 1994) during which time geoduck harvest was allowed under state regulations. In addition to recording the previously described eagle behavior and human activity information, we measured the distance of all perch and foraging locations from the center of harvest activity to the nearest 100 m. The geometric center of harvest activity was determined subjectively based on the locations of stationary boats during disturbance bouts. Harvest boats typically arrived at beginning of the harvest period, anchored, and remained stationary until the completion of the day's activities. A compliance boat from the WDNR accompanied harvest boats on a daily basis. Because monitoring of harvest activities from compliance boats is standard operating procedure for WDNR, we included compliance boats in tallies with harvest boats for all analysis even though they were not engaged in harvest. We used range-finders were used to verify boat locations.

To assess geoduck boat presence on temporal patterns of eagle foraging, we regressed EAMs (total activity time, search-capture time) and number of foraging attempts on GAMs, BAMs, and number of harvest boats for harvest days. Paired T-tests were conducted to assess differences in mean durations of EAMs and number of foraging attempts between harvest and non-harvest days. T-tests were also used to compare total HAMs between weekend non-harvest and weekday harvest bouts (excluding geoduck harvest) to evaluate whether human activity increased on weekends. To assess hourly feeding patterns, we regressed time of day on foraging frequency to see if eagles shifted feeding times on harvest days. Also, on two harvest and non-harvest days at the Squamish Harbor territory we conducted 12-hour observations to determine if eagles shifted foraging outside of the observation period. Numbers of pre- and post-bout foraging attempts were compared with a chi-square contingency test. Standard deviations are reported with all means.

Spatial relationships between eagle foraging and geoduck harvest activities were evaluated with chi-square contingency tests. We compiled total EAMs, search-capture EAMs, the number of foraging attempts, the number of perch visits, and the number of overflights eagle made in each 100 m zone from the center of geoduck activity. Comparisons of these variables were made between non-harvest and harvest days between 5, 400 m increments (e.g. 0-400 m to > 1600 m), and for the 4, 100 m increments up to 400 m. The 400 m zonation was selected prior to analyses, based on the findings of McGarigal et al. (1991) that boating activities were significantly less influential on foraging bald eagles > 400 m away. We plotted harvest and non-harvest day foraging locations using program HOME RANGE (Ackerman et al. 1989) for visual comparisons of center of foraging activity, and core foraging area shape and size, using fifty-percent harmonic mean contours.

RESULTS

Eagle Nest Status, Foraging Behavior, and Home Ranges

We conducted 296 observational bouts, totalling 1896 h during the 2-year study (Table 1). Eagles were observed for 1635 h. In 1993, only two of seven pairs nested successfully, and four of eight pairs were successful in 1994. Of the two pairs associated with geoduck harvest in 1993, only the Squamish Harbor eagles raised young. In 1994, these birds, and those on the second territory associated with harvest, Thorndyke Bay, were inactive but present on the territory throughout the duration of the disturbance study.

We recorded 398 predation attempts at combined territories. Foraging success for attempts with known outcomes (n = 384) was 52%. Of 370 observed predations, 70% were attempts to capture live prey (n = 259), 19% were scavenges (n = 69), and 11% were piracies (n = 42). Eagles pirated osprey (*Pandion haliaeetus*) most often (60%), as well as gulls (*Larus* spp.) (24%), river otters (*Lutra canadensis*) (7%), other eagles (5%), and Northwestern crows (*Corvus caurinus*)(3%). We identified 308 prey items to class: 85% were fish (n = 261), 15% were birds (n = 46), and < 1% were mammals (n =1) and crustaceans (n = 1). Thirty-two of the predated birds were gulls and 1 was a scoter (*Melanitta* spp.). Additionally, we identified a glaucous-winged gull (*Larus glaucescens*) and a great blue heron (*Ardea herodias*) from prey collected under nest trees. Eleven of the identified fish were starry flounders (*Platichthys stellatus*), 4 were skates (*Raja* spp.), and 1 was a shark (family Squalidae).

Home ranges of the eight pairs of eagles ranged in size from 1.12 to 14.10 km^2; core areas were between 0.27 to 4.19 km^2 in size (Appendices B-I). Home ranges of the Squamish Harbor and Thorndyke Bay eagles in 1993 (11.98 and 4.28 km^2, respectively) were slightly larger than ranges for these pairs in 1994 (9.08 and 3.41 km^2, respectively). Size differences resulted primarily from the longer period of observation dates in 1993 (Table 1).

General Human and Eagle Activity Relationships

Activity Levels and Active Eagle Responses.--Excluding observer activities, we identified 1014 activities that were categorized into 16 types of human activity throughout all eagle

Table 2. Human activity levels and distances of activities to eagles and eagle nests for disturbed and non-disturbed eagles in Puget Sound, Washington, 1993-94.

Type	Freq[a] (%)	Mean no. /event	Total activity minutes (%)[b]	Mean activity minutes/event	Flush response Freq. (%)	Flush response Dist.[c] to eagle (m)	Flush response Dist. to nest (m)	No flush response Freq. (%)	No flush response Dist. to eagle (m)	No flush response Dist. to nest (m)
Boat										
Clam boat	387 (38)	1	77087 (25)	199	1 (3)	-	-	337 (39)	580±432	674±256
Motor boat	307 (30)	1	35332 (11)	115	7 (21)	41±21	512±330	255 (30)	421±355	531±265
Canoe/kayak	6 (<1)	2	289 (<1)	48	0 (0)	-	-	4 (<1)	650±304	650±304
Pedestrian										
Beachcomber	78 (8)	4	53185 (17)	681	12 (35)	27±18	681±318	56 (7)	247±302	462±305
Clammer	72 (7)	5	53864 (17)	748	7 (21)	38±21	336±297	64 (8)	283±384	458±362
Oyster	50 (5)	2	14251 (5)	285	2 (6)	-	-	44 (5)	251±230	164±196
Picnic/party	36 (4)	7	41801 (13)	1441	0 (0)	-	-	30 (4)	464±510	385±215
Miscellaneous	13 (1)	6	16819 (5)	1294	2 (6)	-	-	11 (1)	164±103	600±344
Aircraft										
Military	12 (1)	1	195 (<1)	16	0 (0)	-	-	11 (1)	251±230	164±196
Light fixed-wing	16 (2)	1	229 (<1)	14	2 (6)	-	-	13 (2)	473±313	445±186
Helicopter	5 (<1)	1	62 (<1)	12	0 (0)	-	-	4 (<1)	716±490	525±548
Noise										
Construction	4 (<1)	1	725 (<1)	181	0 (0)	-	-	4 (<1)	573±623	366±205
Chainsaw	2 (<1)	1	19 (<1)	10	0 (0)	-	-	2 (<1)	-	-
Lawnmover	1 (<1)	1	19 (<1)	19	0 (0)	-	-	1 (<1)	-	-
Automobile	2 (<1)	1	70 (<1)	35	0 (0)	-	-	1 (<1)	-	-
Other	23 (2)	4	18580 (6)	808	1 (3)	-	-	19 (2)	158±177	318±247
Total	1014		312528		34			856		

[a]Differences between frequencies of human activities and frequencies of responses represent human activities that occurred in the absence of eagles.
[b]1 activity minute = 1 unit of activity conducted for 1 minute.
[c]$\bar{x} \pm SD$.

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Pedestrian										
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Clammer	72 (7)	5	53864 (17)	748	7 (21)	38±21	336±297	64 (8)	283±384	458±362
Oyster	50 (5)	2	14251 (5)	285	2 (6)	-	-	44 (5)	251±230	164±196
Picnic/party	36 (4)	7	41801 (13)	1441	0 (0)	-	-	30 (4)	464±510	385±215
Miscellaneous	13 (1)	6	16819 (5)	1294	2 (6)	-	-	11 (1)	164±103	600±344
Aircraft										
Military	12 (1)	1	195 (<1)	16	0 (0)	-	-	11 (1)	251±230	164±196
Light fixed-wing	16 (2)	1	229 (<1)	14	2 (6)	-	-	13 (2)	473±313	445±186
Helicopter	5 (<1)	1	62 (<1)	12	0 (0)	-	-	4 (<1)	716±490	525±548
Noise										
Construction	4 (<1)	1	725 (<1)	181	0 (0)	-	-	4 (<1)	573±623	366±205
Chainsaw	2 (<1)	1	19 (<1)	10	0 (0)	-	-	2 (<1)	-	-
Lawnmover	1 (<1)	1	19 (<1)	19	0 (0)	-	-	1 (<1)	-	-
Automobile	2 (<1)	1	70 (<1)	35	0 (0)	-	-	1 (<1)	-	-
Other	23 (2)	4	18580 (6)	808	1 (3)	-	-	19 (2)	158±177	318±247
Total	1014		312528		34			856		

[a]Differences between frequencies of human activities and frequencies of responses represent human activities that occurred in the absence of eagles.
[b]1 activity minute = 1 unit of activity conducted for 1 minute.
[c]$\bar{x}\pm SD$.

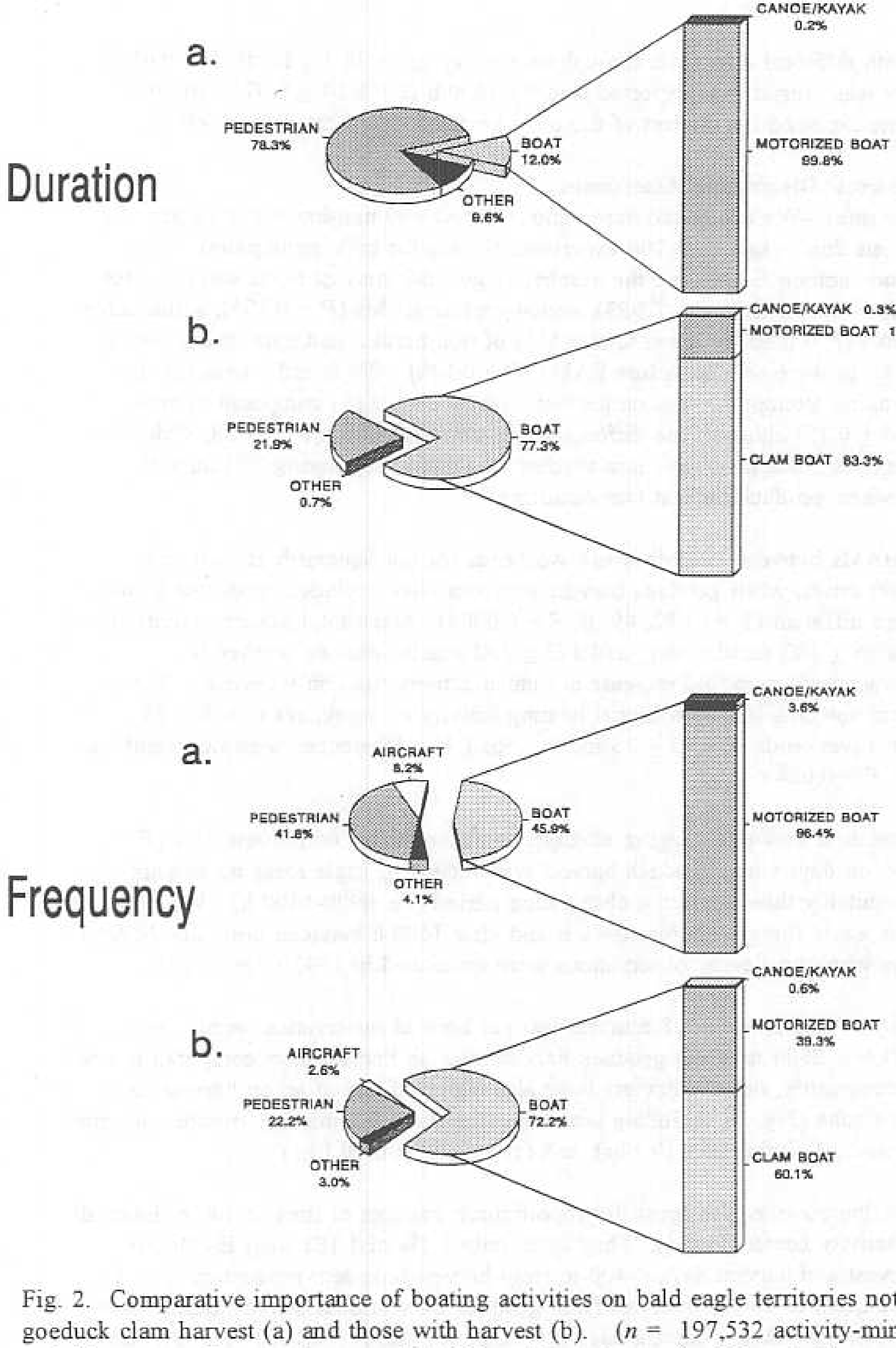

Fig. 2. Comparative importance of boating activities on bald eagle territories not experiencing goeduck clam harvest (a) and those with harvest (b). (n = 197,532 activity-minutes for 122 activities on non-harvest sites; n = 114,996 activity-minutes for 892 activities on harvest sites).

Eagles foraged with different intensities throughout the day (χ^2 = 28.47, 15 df, P = 0.019). Foraging intensity was greater than expected prior to 1000 h ($\bar{x}$ = 0.14 $\pm$ 0.07 attempts/hr obs.), and less than expected for the rest of the day ($\bar{x}$ = 0.02 $\pm$ 0.02 attempts/hr obs.).

Geoduck Clam Harvest Disturbance Assessment

Temporal Relationships.--We conducted observations during 100 non-harvest days and 100 harvest days for combined years (n = 100 experimental days for both eagle pairs). There were no correlations among GAMs and the number of geoduck harvest boats and the three dependent variables: total EAMs (P = 0.993), search-capture EAMs (P = 0.105), and number of foraging attempts (P = 0.807). Mean total EAMs of non-harvest and harvest days were similar (P = 0.308), as were search-capture EAMs (P = 0.148). We found a tendency for reduced mean foraging attempts/hr obs. on harvest days (0.15 $\pm$ 0.19) compared to non-harvest days (0.20 $\pm$ 0.15) although the difference was not significant (T = -1.58, 49df, P = 0.060). That is, eagles made about one less attempt to capture prey during 20 hours of observation time when geoduck harvest was occurring.

Comparisons of HAMs between weekdays and weekends for the Squamish Harbor and Thorndyke Bay territories, when geoduck harvest activities were excluded, indicated human activity levels were different (T = -3.82, 49 df, P = 0.0002). Mean total human activity times for weekdays was 76 $\pm$ 102 min/hr. obs., and 173 $\pm$ 202 min/hr. obs. on weekends. Therefore, there was over a two-fold increase in human activity time on weekends. There was also a tendency towards less recreational boating activity on weekdays ($\bar{x}$ = 8 $\pm$ 28 min/hr. obs.) versus weekends ($\bar{x}$ = 18 $\pm$ 38 min/hr. obs.), but differences were not significant (T = -1.55, 49 df, P = 0.064).

We found no correlation between foraging attempts and time of day on harvest days (P = 0.429). Therefore, on days when geoduck harvest was occurring, eagle foraging attempts were distributed equitably throughout the observation period (i.e. 0900-1500 h). We found no significant shifts in eagle foraging before 0900 h and after 1600 h between the 2 non-harvest and 2 harvest days when whole-day observations were conducted in 1993 (P = 0.917).

Spatial Relationships.--Eagles spent 5.8 minutes less per hour of observation within the observable area (i.e. < 2300 m) from geoduck harvest sites on harvest days compared to non-harvest days. Consequently, other behaviors were also observed less often on harvest days within this distance zone (Fig. 3), including search-capture time (6.9 min/hr), number of perch visits (0.2/hr), number of flight visits (0.7/hr), and forage attempts (0.1/hr).

Within the observation zone, eagles spent disproportionate amounts of time at 400 m intervals from the harvest activity center (Fig. 4). They spent only 1.2% of 1,181 total EAMs for combined non-harvest and harvest days < 400 m from harvest boat activity centers (Fig. 5). Total EAMs eagles spent at 400-m intervals from geoduck harvest boat activity centers were different between non-harvest and harvest days (χ^2 = 354.48, 4df, P < 0.0001; Fig. 3). On harvest days, eagles spent significantly fewer minutes than expected < 400 m from activity

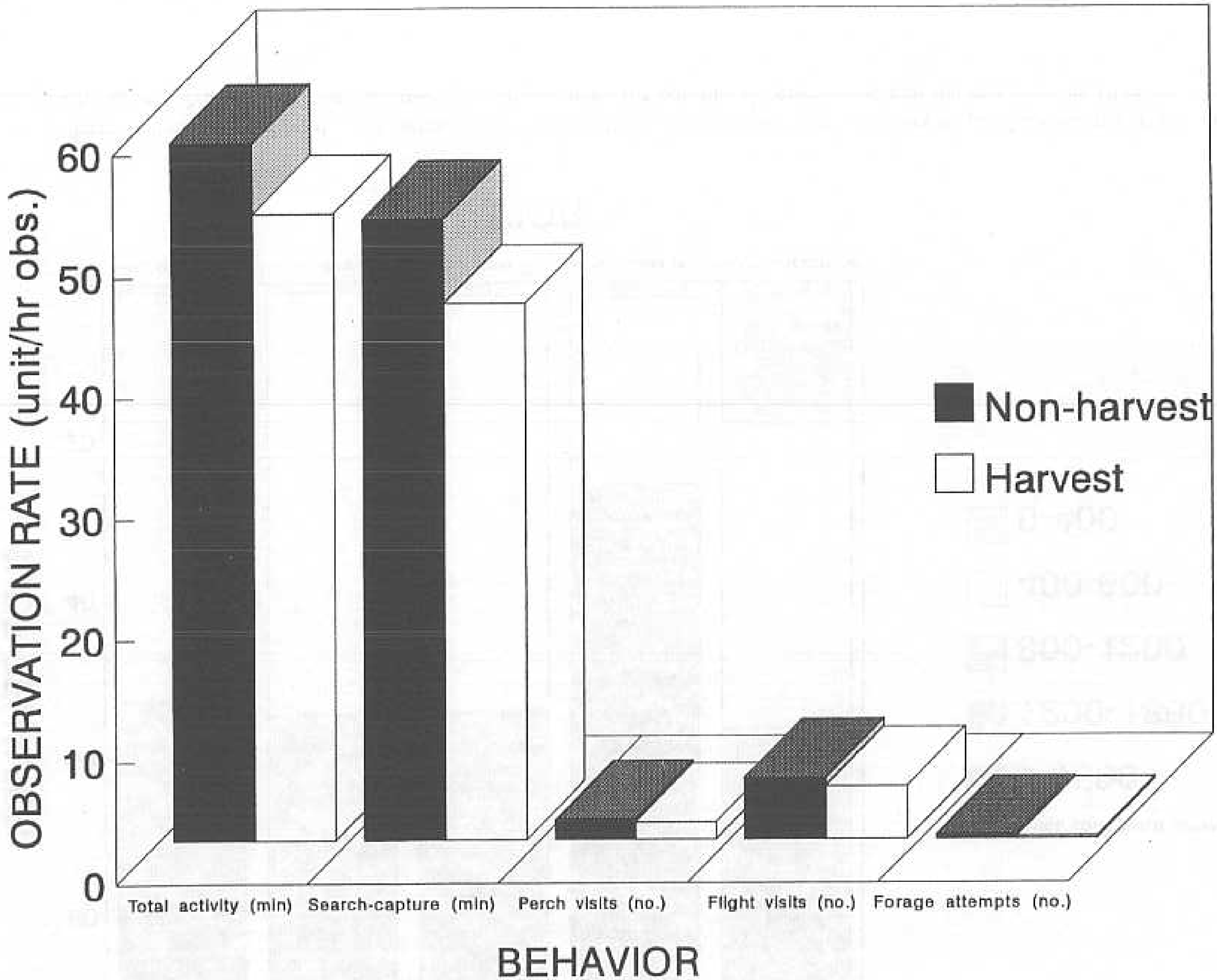

Fig. 3. Differences in bald eagle behavior <2300 m from geoduck clam harvest for non-harvest and harvest days on Hood Canal, Washington, 1993-94.

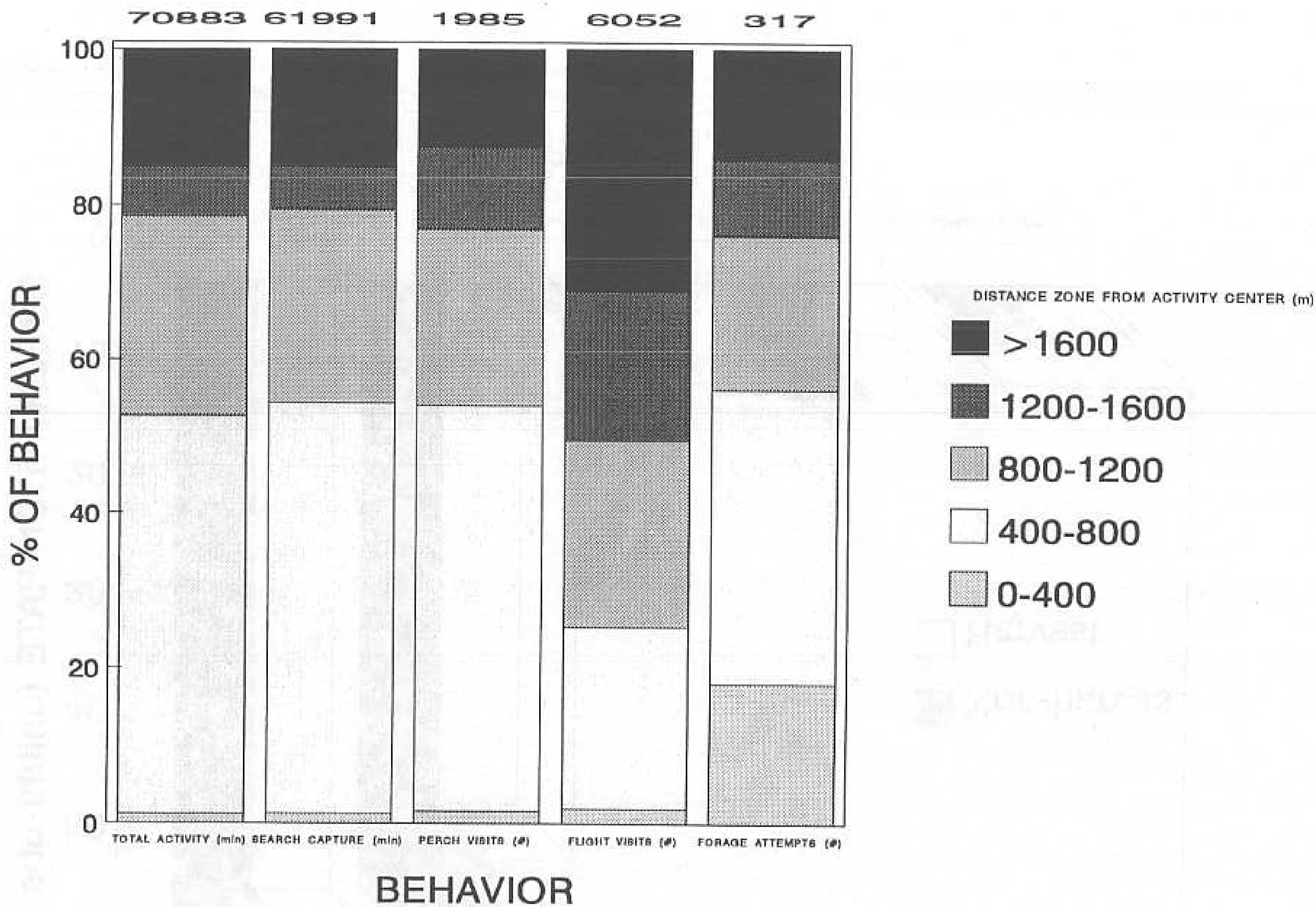

Fig. 4. Relative importance of bald eagle behaviors at different distance intervals from centers of geoduck clam harvest on Hood Canal, Washington. Numbers above bars indicate sample sizes for combined non-harvest and harvest days in 1993-94.

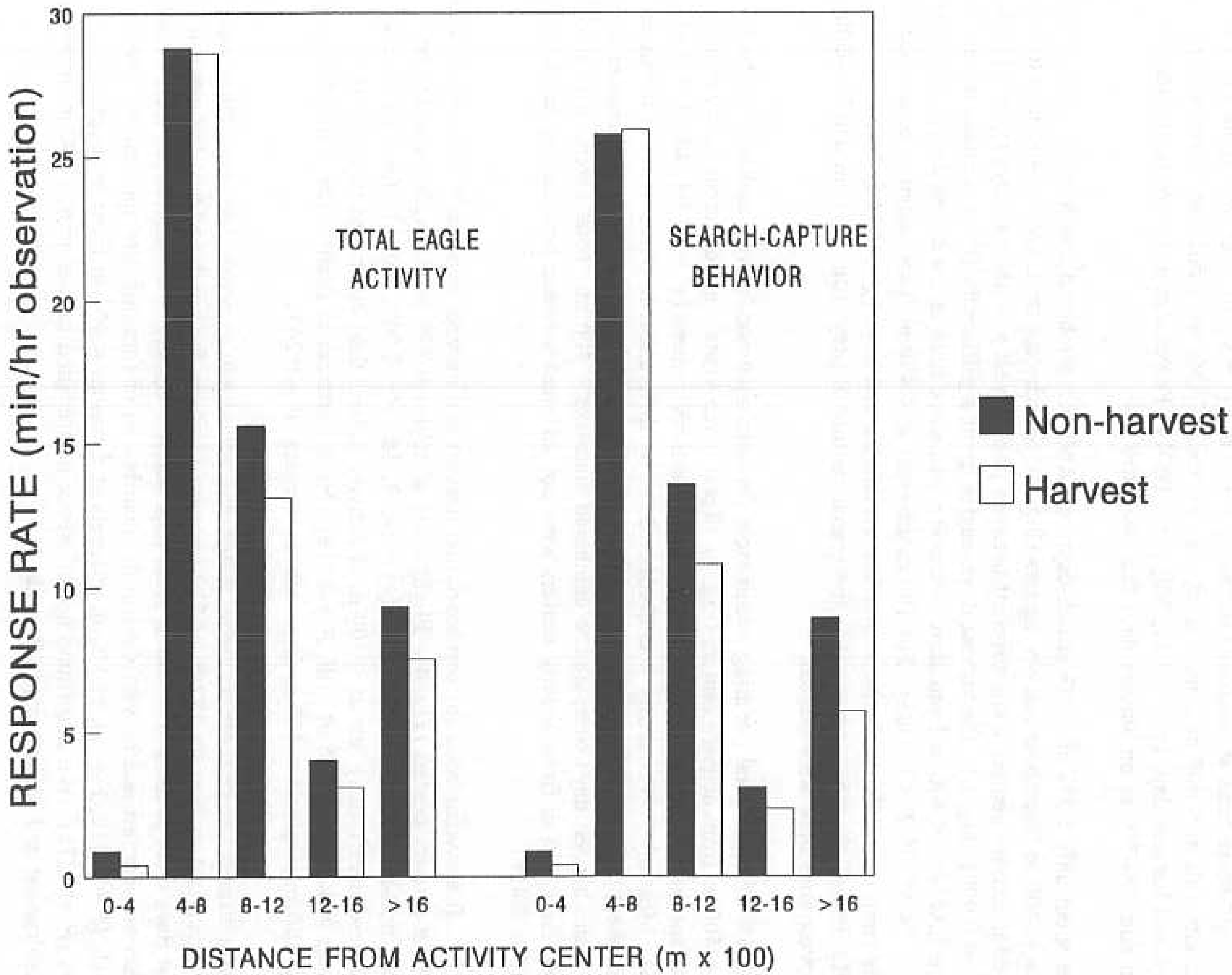

Fig. 5. Comparisons of response rates of bald eagles between non-harvest and harvest periods for geoduck clams on Hood Canal, Washington, 1993-94.

centers, and more time at combined distances > 400 m (χ^2 = 90.40, 1 df, P < 0.0001). For 100 m intervals at < 400 m from activity centers, total EAMs were different between non-harvest and harvest days (χ^2 = 57.21, 3df, P < 0.0001). Fewer minutes were spent from < 100 m and 200-300 m on harvest days than we expected.

Eagles spent only 1.3% of 1,033 search-capture EAMs for combined non-harvest and harvest days at < 400 m from boat activity centers (Fig. 4). Search-capture EAMs at 400 m intervals from boat activity centers were different between non-harvest and harvest days (χ^2 = 510.62, 4df, P < 0.0001, Fig. 5). On harvest days, eagles spent significantly fewer minutes in search-capture EAMs at < 400 m from activity centers, and more time at combined distances > 400 m (χ^2 = 74.67, df, P < 0.0001). For 100 m intervals at < 400 m from activity centers, search-capture time was different between non-harvest and harvest days (χ^2 = 61.85, 3df, P < 0.0001). Fewer minutes were spent in the search-capture of prey from < 100m and 200-300 m on harvest days than we expected.

Only 1.6% of 1,985 total perching occurrences for combined non-harvest and harvest days were < 400 m from activity centers (Fig. 4). Total perch visits were different between non-harvest and harvest days at 400 m intervals from activity centers (χ^2 = 11.04, 4df, P = 0.026; Fig. 6). Most of the variability was accounted for by differences in perch visits at distances > 400 m; there was no difference in perch visits at < 400 m from activity centers between non-harvest and harvest days compared to combined distances > 400 m. Total perch visits at 100 m intervals < 400 m from activity centers were not different between non-harvest and harvest days (P = 0.458).

For 6,052 flight visits/zone for combined non-harvest and harvest days, only 1.9% were < 400 m of boat activity centers (Fig. 4). Flight visits of eagles at 400 m intervals were different between non-harvest and harvest days (χ^2 = 14.13, 4df, P = 0.007; Fig. 6). On harvest days, eagles flew significantly less at < 400 m of activity centers than compared to combined distances > 400 m (χ^2 = 5.61, 1df, P = 0.018). No differences in flight visits were identified among 100 m intervals < 400 m from activity centers (P = 0.243).

Foraging attempts were more equitably distributed across 400 m zones than were other eagle behavior variables (Fig. 4); 18.0% of 317 foraging locations for combined non-harvest and harvest days were located at < 400 m from boat activity centers. No differences were found between non-harvest and harvest days in the distribution of foraging attempts among 400 m intervals (P = 0.118; Fig. 6), or 100 m intervals at distances < 400 m from boat activity centers (P = 0.271). We also found no difference in predation tactics among 100 m intervals for non-harvest and harvest days (P = 0.810).

Core foraging areas, represented by 50% utilization contours, were similar in shape and location between non-harvest and harvest days for both the Thorndyke Bay and Squamish Harbor territories 1993 and 1994 combined (Figs. 7 and 8). Core foraging areas on non-harvest days were 24% smaller than harvest days for the Thorndyke Bay eagles (i.e. non-

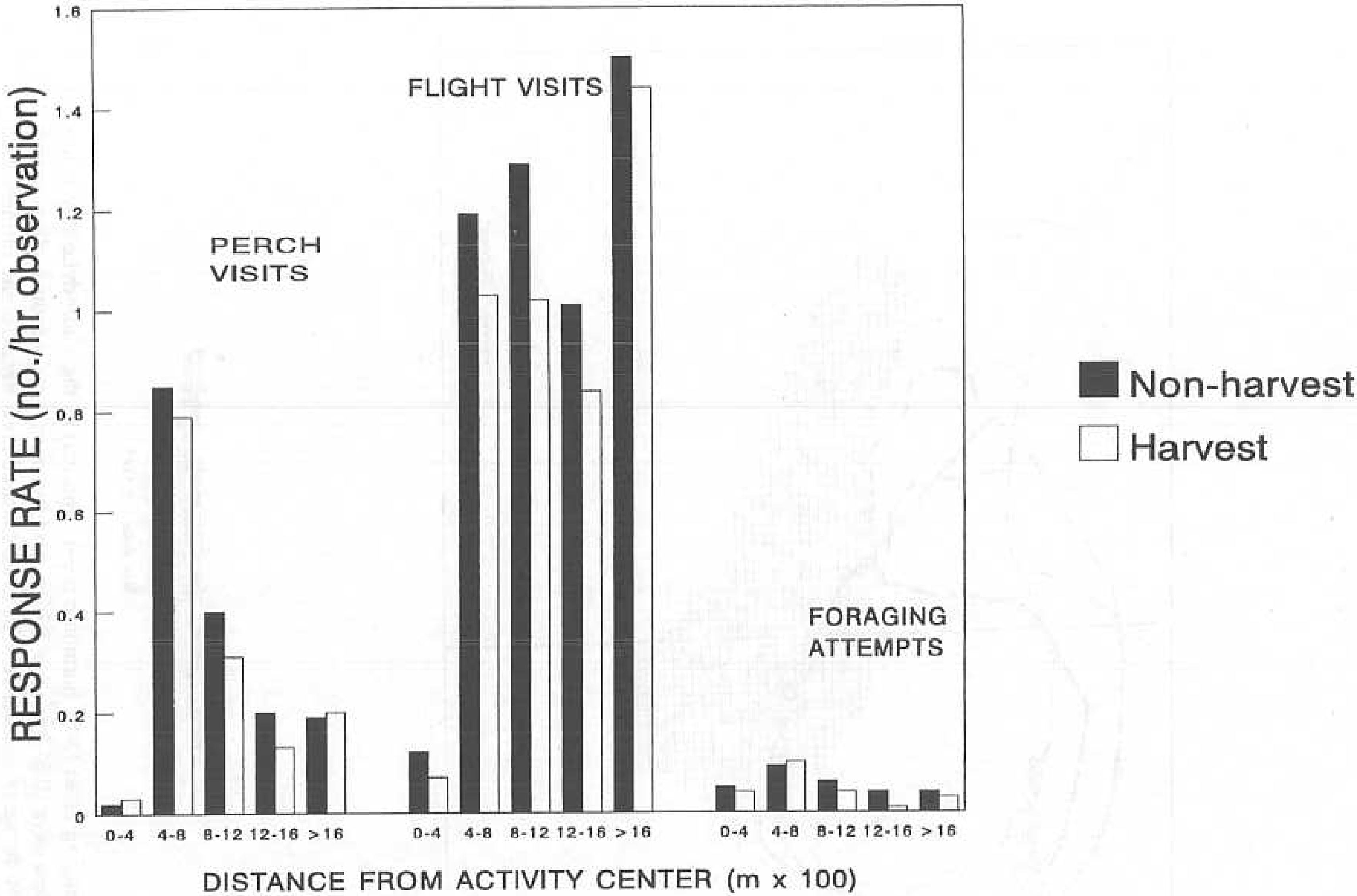

Fig. 6. Comparisons of response rates of bald eagles between non-harvest and harvest periods for geoduck clams in Hood Canal, Washington, 1993-94.

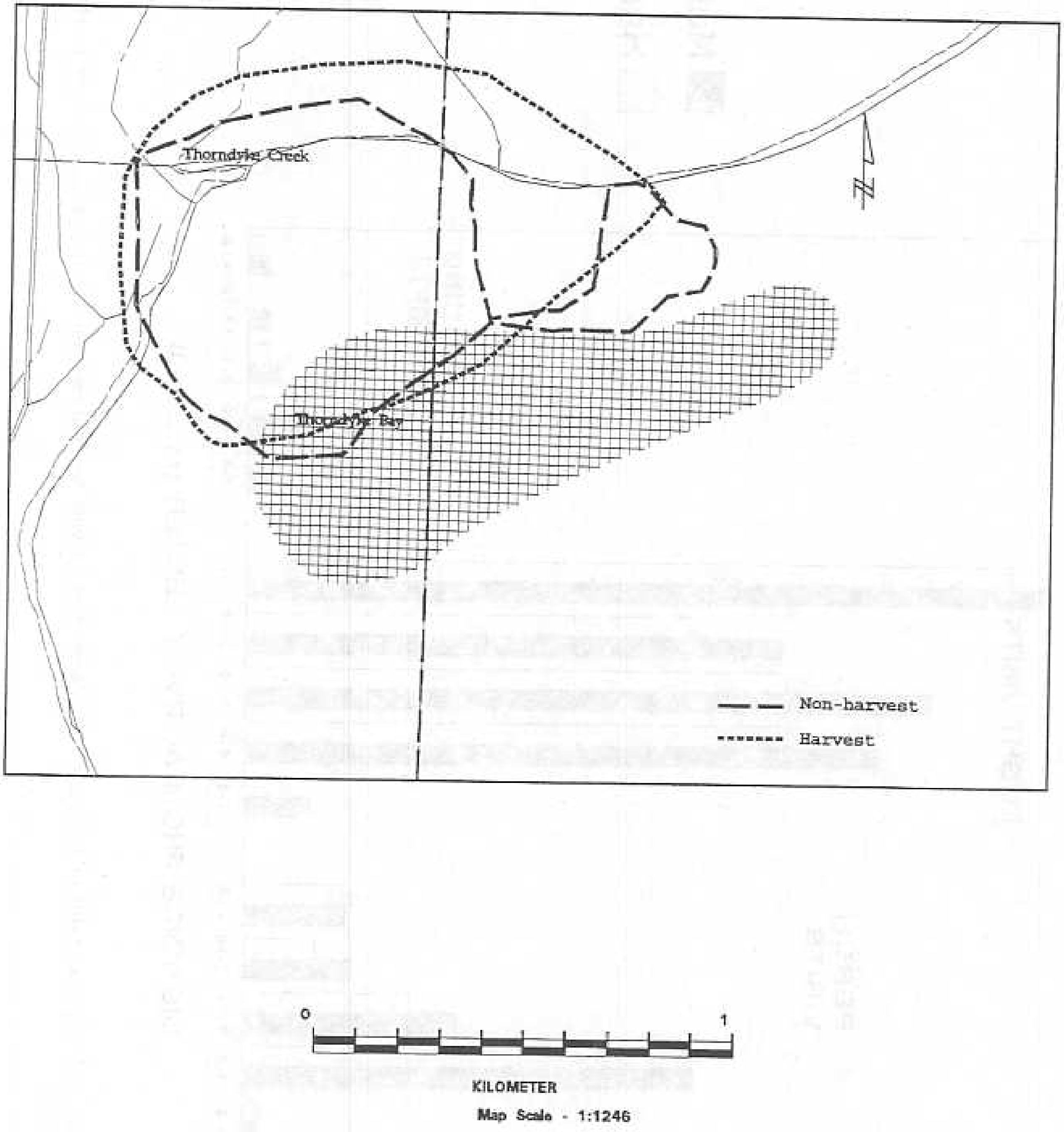

Fig. 7. Core foraging areas (50% harmonic mean contours) of the Thorndyke Bay bald eagles during non-harvest days (0.62 km^2; n = 80 foraging locations), and geoduck clam harvest days (0.82 km^2; n = 66 foraging locations). The cross-hatched area identifies the primary clam harvest zone.

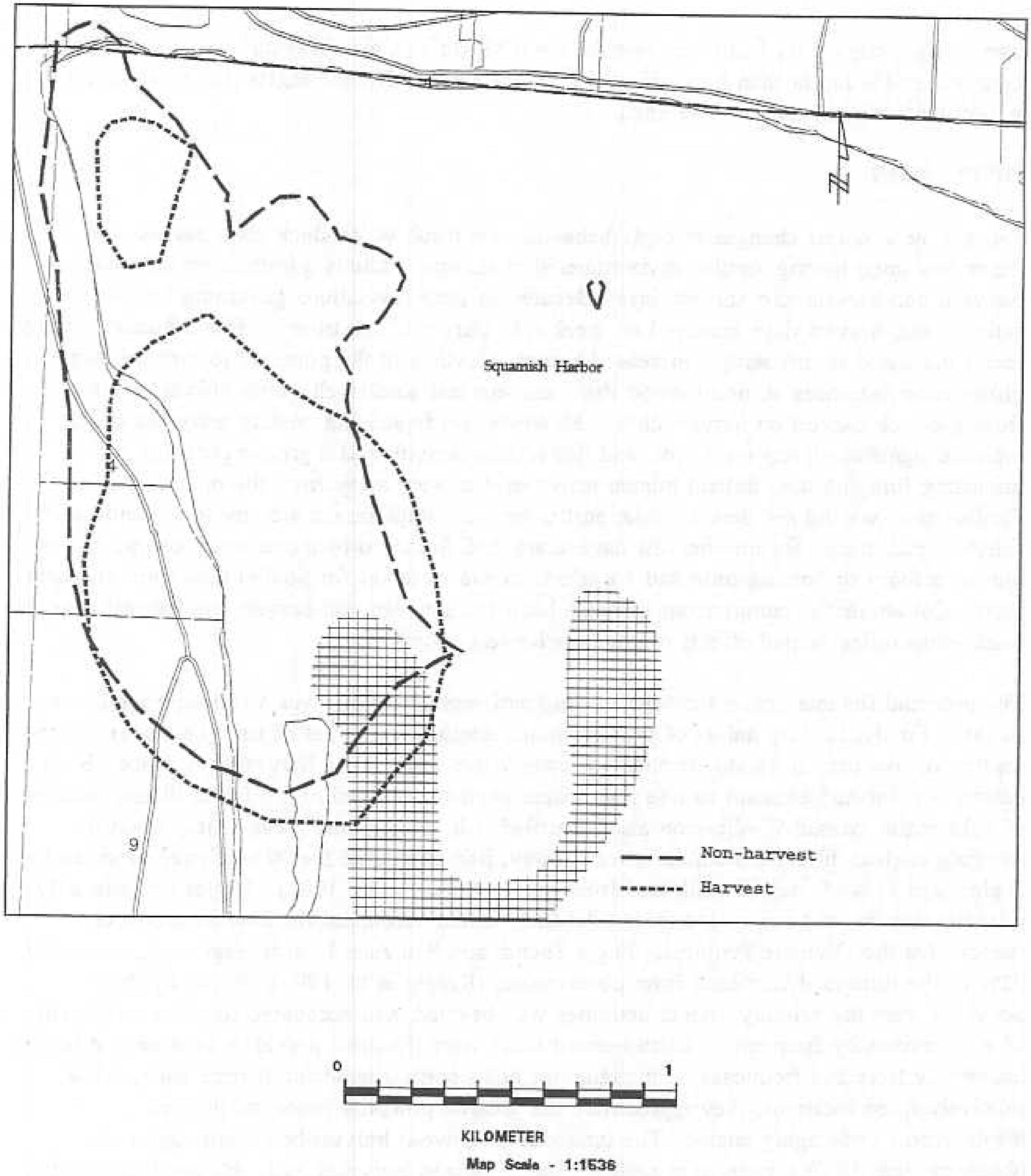

Fig. 8. Core foraging areas (50% harmonic mean contours) of the Squamish Harbor bald eagles during non-harvest days (1.69 km^2; n = 92 foraging locations), and geoduck clam harvest days (1.29 km^2; n = 79 foraging locations). The cross-hatched area identifies the primary clam harvest zone.

harvest days days = 0.62 km^2; harvest days = 0.82 km^2). Core foraging areas on non-harvest days were 31% larger than harvest days for the Squamish Harbor eagles (i.e. non-harvest days = 1.69 km^2; harvest days = 1.29 km^2).

DISCUSSION

Our ability to detect changes in eagle behavior as a result of geoduck clam harvest was dependent upon having similar environmental conditions, including human activity levels, between non-harvest and harvest days. Because of state regulations governing harvest activity, non-harvest days occurred on weekends, during which time we found human activity levels increased significantly. Increased human activity had the potential to increase eagle disturbance responses on non-harvest days, and conceal actual behavioral effects resulting from geoduck harvest on harvest days. However, we found that boating activities did not increase significantly on weekends, and this human activity had a greater potential for impacting foraging than upland human activities that were away from the open water. Furthermore, we did not detect a relationship between total human activity levels and eagle behavior parameters for non-harvest days alone, and found no temporal relationships among human activity or boating time and 3 eagle response variables for pooled data from all eagle pairs. Consequently, comparisons of eagle behavior between non-harvest and harvest days are believed to reflect actual effects of geoduck harvest activities.

The potential for interaction between boating and eagle activities was a consequence of two factors. Firstly, feeding habits of the population emphasized a diet of fish (i.e. 85%) and the capture of live prey in relatively shallow, open-water where clam harvest took place. Such habitat was located adjacent to tide flats where eagles scavenged prey. Other dietary studies of bald eagles coastal Washington also identified fish and subtidal areas as important for foraging eagles. In the Columbia River Estuary, fish accounted for 90% of prey captured by eagles, and 71% of prey by collected from nests (Watson et al. 1991). Eagles fed primarily in shallow water and scavenged from tidal flats, which accounted for 24% of predation tactics. On the Olympic Peninsula, Puget Sound, and San Juan Islands, eagles consumed fish 92% of the time as determined from observations (Knight et al. 1990). Secondly, boat activities were the primary human activities we observed, and accounted for over two-thirds of all activities by frequency. Clam harvest boats were the most prevalent boating and human activity by time and frequency. Since harvest boats spent a majority of time anchored at relatively fixed locations, they represented the greatest potential source of passive displacement to foraging eagles. The interactions between harvest boats and eagles we observed were, in fact, passive in nature. For all human activities, only 4% resulted in active eagle responses (i.e. flushes), and geoduck clam harvest was an insignificant source of that disturbance, accounting for only 1 of 34 flushes. While we were unable to observe geoduck boats the entire time they left docks in transit to harvest sites, this was an insignificant portion of the total time harvest boats were on the water, and no eagles were seen responding to moving harvest boats. At the human activity levels we observed, moving recreational boats and pedestrians (primarily beachcombers and clammers on tide flats), presented the most significant source of direct disturbance to eagles. McGarigal et al. (1991) also found that the primary disturbances of foraging eagles on the Columbia River Estuary were the result of active flushes from moving boats (6.4%), rather than anchored boats (2.3%). Moving boats, presented a greater source of active disturbance because they typically impacted a larger area and were more likely to encounter eagles, as Stalmaster (1989) also observed for wintering eagles on the Skagit River in northwest Washington.

The indirect eagle responses from clam harvest that we documented were of two types: increased presence of eagles > 2300 m from harvest tracts, and behavioral changes at distances < 2300 m away. The relevance of the former response is that harvest activity within a relatively small area (e.g. < 0.5 km^2) caused eagles to avoid the large embayments (i.e. Squamish Harbor and Thorndyke Bay) and core foraging areas (e.g. avg. 1.1 km^2) for an average of 5.8 minutes for each hour of observation. We were unable to document movements of birds outside of the viewing area because they were not radioed. Because bald eagles may have more than one foraging area on a given territory (Watson and Anthony 1986), the eagles may have spent time at a secondary foraging site. The consequence of eagles being displaced for such a short amount of time from the primary foraging site is not significant, but the effects we observed would probably have been greater had the harvest tracts been located at the center of the core foraging areas. As noted by McGarigal et al. (1991), a few stationary boats at the centers of foraging sites on an eagle territory could disrupt feeding behavior. Since, as demonstrated for bald eagles, supplemental feeding may enhance nesting success (Hansen 1987), and there are minimum levels of food required for raptors to breed and raise young (Ridpath and Brooker 1986), reduced feeding behavior could ultimately lead to reduced productivity.

For activities at < 2300 m from harvest tracts, foraging attempts were the only eagle behavior parameter that occurred frequently and in close enough proximity to geoduck boats to be impacted by harvest activities. On harvest days eagles foraged consistently throughout the observation period, which was in contrast to feeding behavior on non-harvest days and the other territories we studied, as well as other eagle populations where foraging attempts were most frequent in the morning hours (Harmata 1984, Watson et al. 1991). McGarigal et al. (1991) suggested that early morning foraging of eagles on the Columbia River Estuary resulted in part from the absence of recreational boaters during the early part of the day. Because we did not observe eagle entire days during harvest periods (except for one bout cycle where we detected no shifts in foraging) it was unclear as to whether eagles may have foraged more prior to 0900 h, when harvest commenced on harvest days. Continued afternoon foraging that we observed on harvest days, and the minor reduction in overall foraging attempts (i.e. 1/20 hr. obs.) compared to non-harvest days, suggested that eagles maintained hourly foraging levels in order compensate for lost foraging effort.

Spatial distribution of foraging attempts < 2300 m from activity centers was not different between non-harvest and harvest days based on analysis of distance intervals and plotting of core foraging areas. Differences may have been evident had harvest activity been located at the centers of the high-use foraging areas. On the Columbia River Estuary, such activity significantly reduced foraging locations at distances < 400 m from activity centers, and apparently caused eagles to move to secondary foraging sites (McGarigal et al. 1991). Changes in sizes of core foraging areas on non-harvest and harvest days were inconsistent between eagle pairs; the core area increased for one pair, and decreased for the other as might be expected, respectively. Causes for the different trends are unknown, but inconsistent responses suggest factors other than clam harvest were involved.

Other eagle behaviors including total activity time, and search-capture time, were different at < 400 m from harvest centers, compared to areas 400-2300 m away. However, because only about 1% of activity time was spent in either behavior at < 400 m from activity centers for both non-harvest and harvest days, these behavioral changes were unimportant to the ecology of these eagle pairs. The same was true for frequencies of perch and flight visits where < 2% of respective activities occurred at < 400 m from activity centers. Higher perching frequency > 400 m from the harvest activity center reflected the fact that most hunting perches were along the shoreline, with the exception of the channel markers at the Squamish Harbor territory. In contrast, considerable hunting on the Columbia River Estuary occurred from within the foraging areas from numerous pilings, channel markers, as well as tide flats (Watson et al. 1991, Garrett et al. 1993). The seasonal decrease in eagle presence near nests for experimental sites was unrelated to harvest activities, and consistent with other studies that have demonstrated declining seasonal nest tenacity (Bowerman 1991, Watson 1994a). Interestingly, the fact that both pairs continued to forage extensively in the bay in years they failed to raise young shows they were not strongly influenced by harvest activities, or were limited in movement by a lack of other foraging areas. Bald eagles without young were less tenacious to perches near nest trees than those with young at the approach of survey helicopters in northwest Washington (Watson 1993).

MANAGEMENT RECOMMENDATIONS

Geoduck clam harvest is unlikely to adversely impact productivity of bald eagles in Washington state based on the levels and types of eagle behavioral responses that we identified, the current state regulations governing harvest, and harvest tract locations. Of the 536 occupied bald eagle territories in 1995, 43 (8%) of these are < 400 m from potential harvest tracts where there is the greatest potential for impact, and 122 (i.e. 23%) are < 1.6 km away (WDNR and WDF 1985). Also, because harvest typically is completed at a given clam bed in < 3 years, and is typically not conducted again for at least 6 years (A. Bradbury, pers. comm.), intensity of this activity is varies annually at given locations relative to other activities such as recreational clamming that can be expected to occur every year. Minimizing the effects of geoduck clam harvest where localized bald eagle breeding is impaired, such as on Hood Canal, is justified, particularly until the causes of chronic reproductive failure are identified and managed.

Stationary boats used for the harvest of geoduck clams are most likely to change the behavior of nesting bald eagles when harvest occurs within the core area where eagles forage, and during the most intense daily foraging period (i.e. prior to 1000 h). Ideally, foraging areas should be identified in the season prior to harvest to determine the amount of overlap with proposed harvest sites. Such information can be determined from relatively short term (e.g. 3-month) observational studies with a sampling intensity similar to ours (e.g. 30 hrs/wk). In the absence of such information, or when overlap is determined, harvest is unlikely to significantly change eagle behavior when harvest intensity is similar to what we observed (i.e. averages about 1-2 boats/episode) and takes place at only one point location within a given eagle territory. Eagle territory boundaries can be approximated by consulting WDFW biologists, and referencing the locations of adjacent eagle nests. Additionally, restricting harvest to after 1000 h will eliminate boating presence during the main foraging period.

Rigorous study of the two eagle territories aided in our ability to detect actual harvest effects for these sites. At the same time, if the small sample was not representative of the population, particularly where geoduck clam harvest is proposed, findings are of limited use for making population recommendations. We suggest application of these findings is most appropriate for other eagle territories that: 1) are situated on tidally-influenced shorelines where embayments provide scavenged as well as live prey. Because geoduck clam harvest is limited to waters > 200 m from shore and < 23m deep (WDNR and WDF 1985), eagles on tide flats will be in relatively close proximity to harvest boats only when tide flats are expansive; 2) are in populations where nesting densities are relatively similar to those we observed, resulting in similarly-sized territories and effective foraging areas. Local densities of raptors, including bald eagles, have been correlated with food supplies (Newton 1979, Newton et al. 1986, Dzus and Gerrard 1993), and for territorial raptors the available hunting range may be limited by active defence of territories (Newton 1979); 3) have nest trees that are not on shorelines directly above (e.g. < 200 m) the proposed harvest site that might affect other behaviors, such as nest attendance, in addition to foraging; and 4) are not associated with unusually high levels of human activity, such as a marina, that might further limit foraging efficiency.

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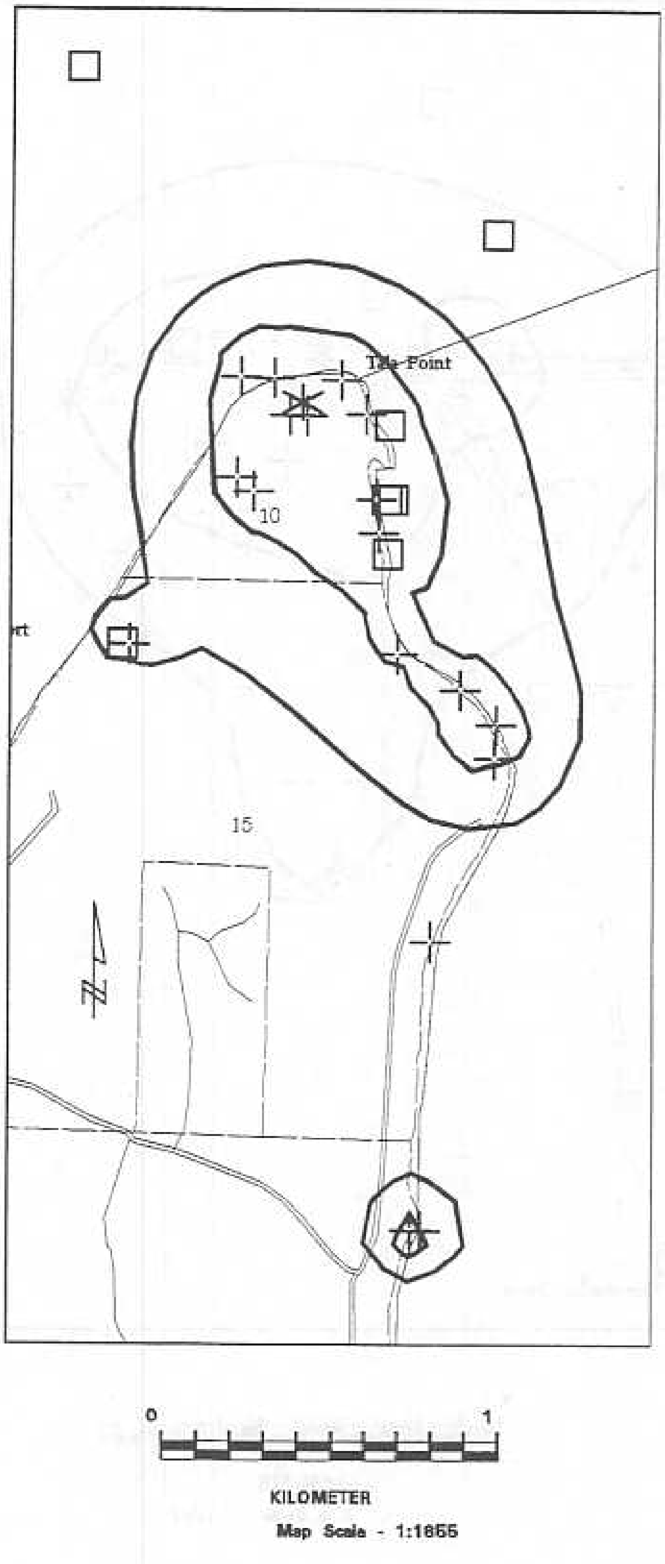
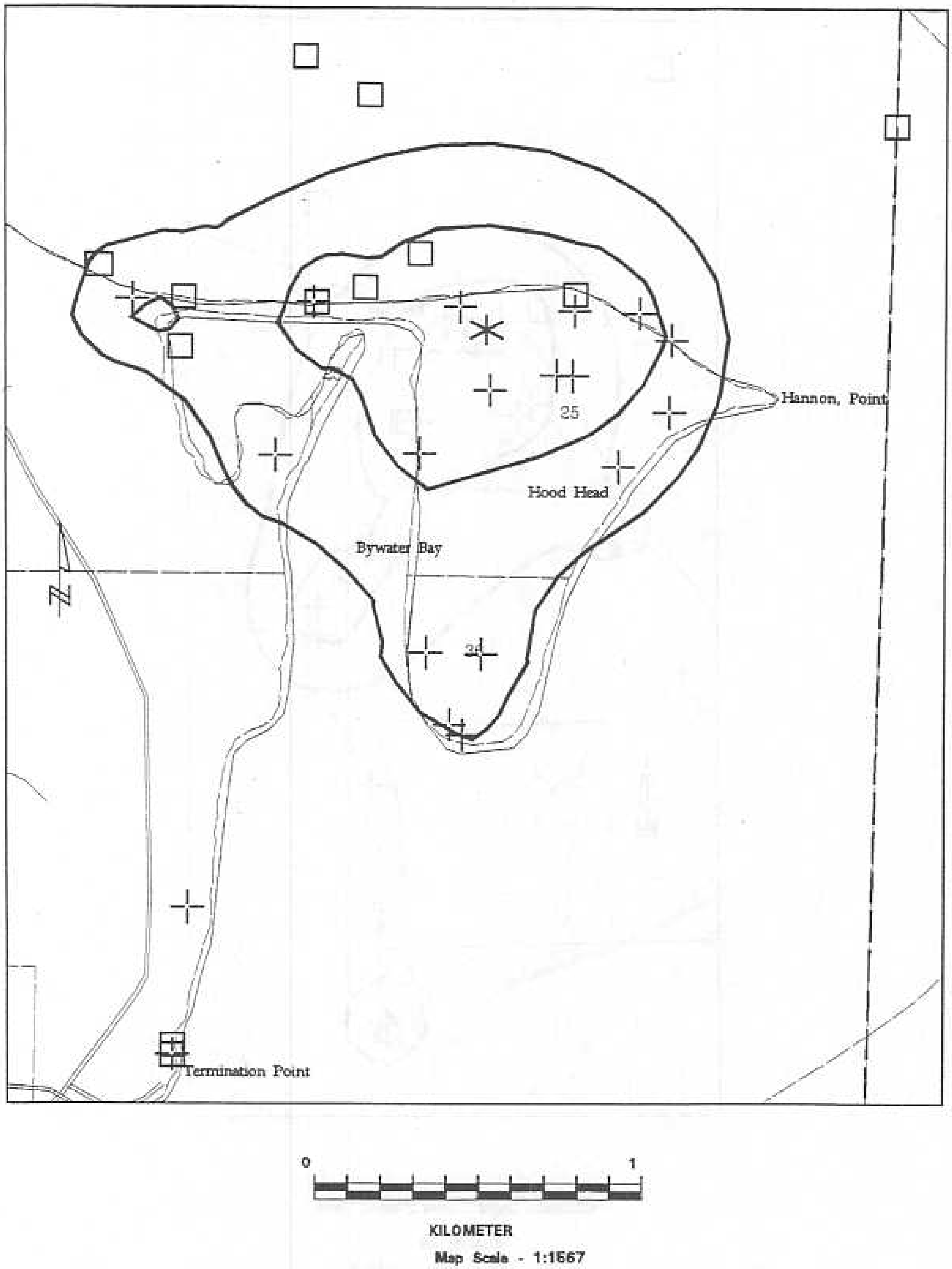
APPENDICES

Appendix A. Factors for which data were collected during observations of bald eagles in Puget Sound, Washington, 1993-94.

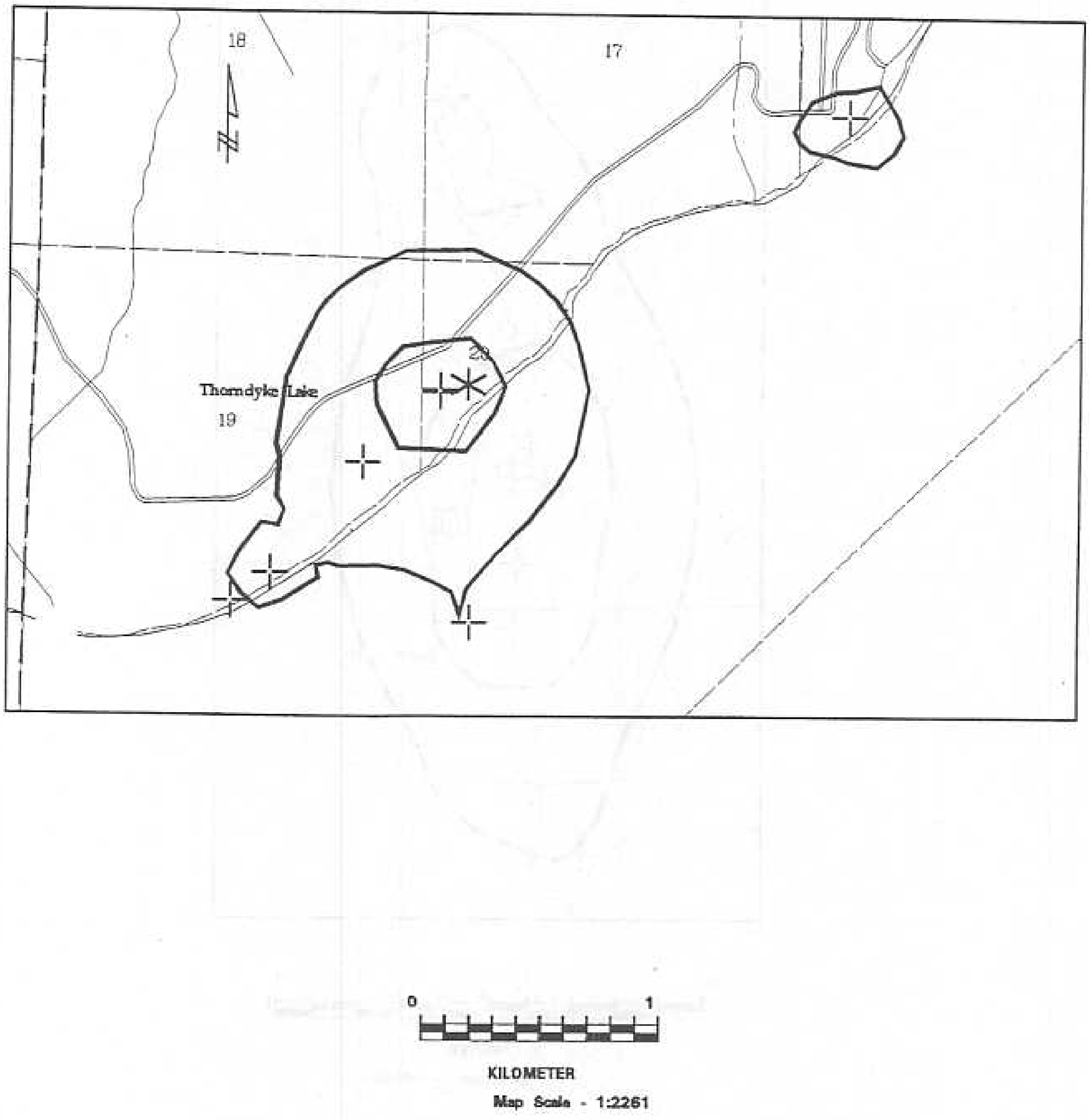
Type	Description	Categories
Eagle Activity	Behavior	perch hunt, loaf, feed self, misc.perch activity, nest build, feed young, incubate, brood, misc. nest activity, direct flight, prey pursuit/delivery, soar, misc. flight, disturbance vocalization, disturbance light attention, disturbance flush/soar, disturbance flush/reperch, disturbance flush/lost
	Perch Zone	$\leq$30, 31-60, 61-120, 121-400, $\geq$400 (m from nest)
	General Habitat	residential, pasture, clearcut, tidal flat, open water, mature forest, young forest, dry sand, other
	Specific Habitat	Doug fir, grand fir, cedar, snag, cottonwood, other tree, piling, unknown, other
	Predation Tactic	direct live, scavenge, pirate, unknown
	Predation Result	successful, unsuccessful, unknown
	Prey Group	fish, mammal, bird, unknown
Weather	Windspeed	calm, breeze, brisk, gust
	Sky (% overcast)	0-4, 5-25, 26-50, 51-75, 76-95, 96-100
	Precipitation	none, occ. drizzle, steady drizzle, occ. heavy rain, heavy rain, sleet, snow
Human Activity	Type	pedestrian, chainsaw, lawnmower/yardwork, construction, recreation, other pedestrian, automobile, boat, aircraft, other
	Motion	slow, moderate, fast
	Noise	soft, medium loud
Disturbance	Response Type	stand on nest, flush/reperch, perch agitation, passive, passive flight, flush/soar flush/lost, vocalization, flew in during bout, aggression w/conspecific



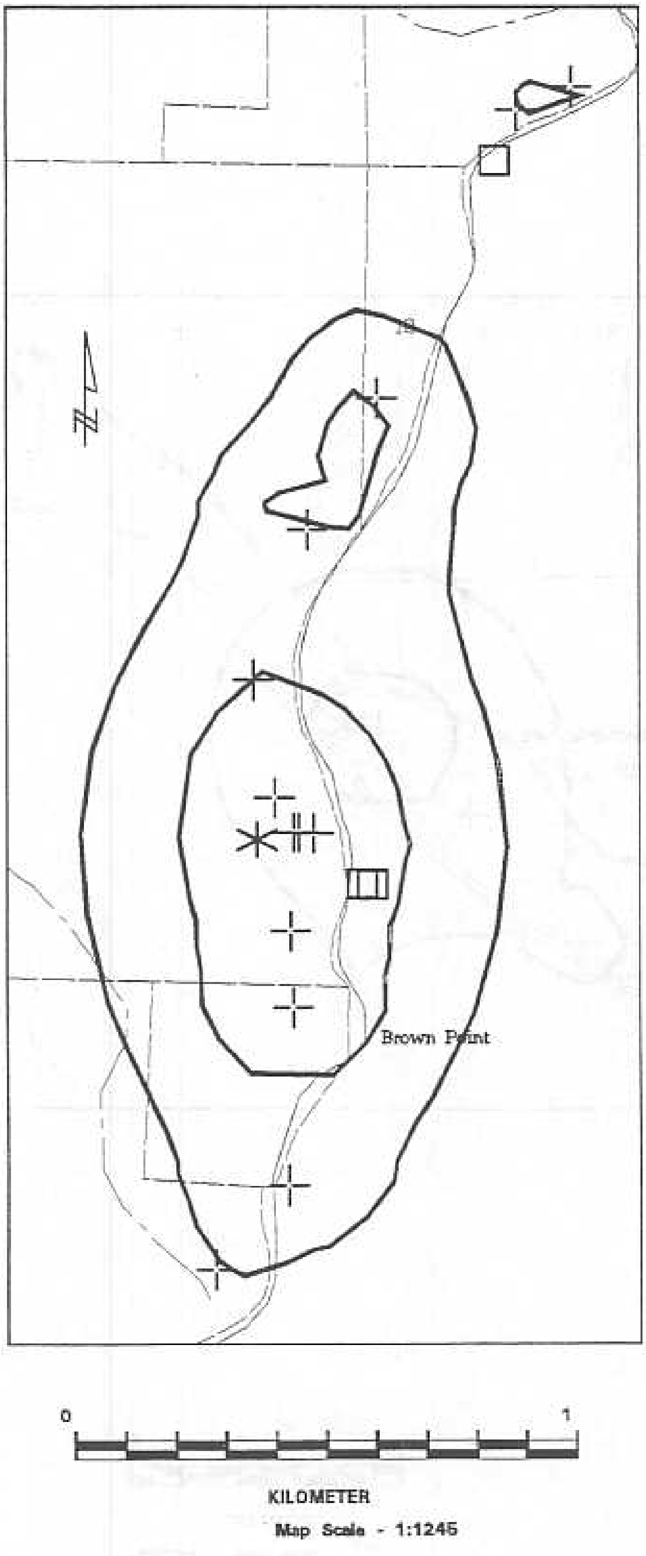
Appendix B. Home range (95% harmonic mean contour; 1.69 km^2) and core areas (59% contours; 0.56 km^2) of the Tala Point bald eagles on Hood Canal, Washington. Crosses indicate perch locations (n = 92), squares identify foraging attempts (n = 7), and the star represents the activity center. Each cross or square may represent >1 location.



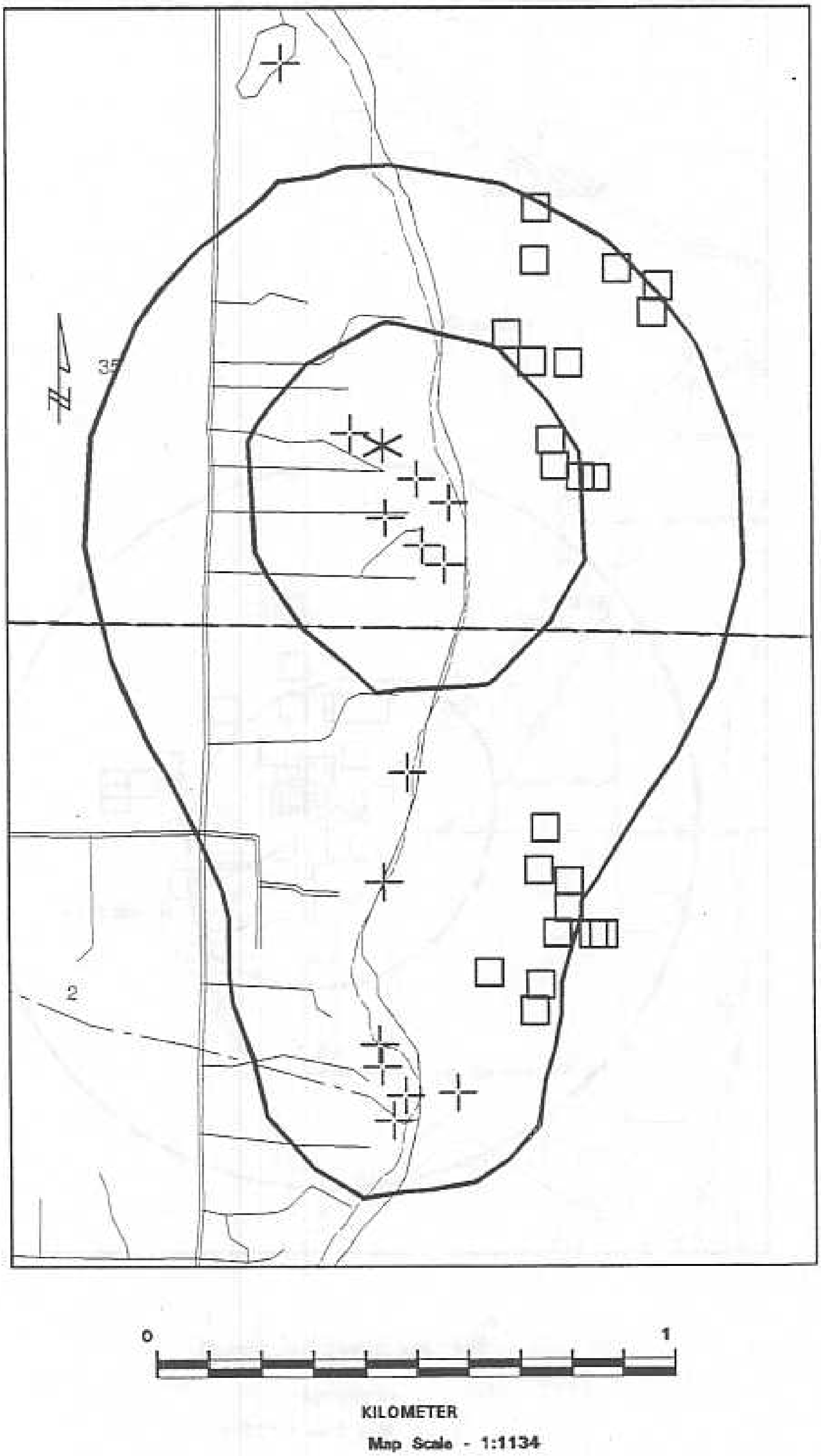
Appendix C. Home range (95% harmonic mean contour; 2.08 km^2) and core areas (56% contours; 0.66 km^2) of the Hood Head bald eagles on Hood Canal, Washington. Crosses indicate perch locations (n = 121) , squares identify foraging attempts (n = 15), and the star represents the activity center. Each cross or square may represent >1 location.



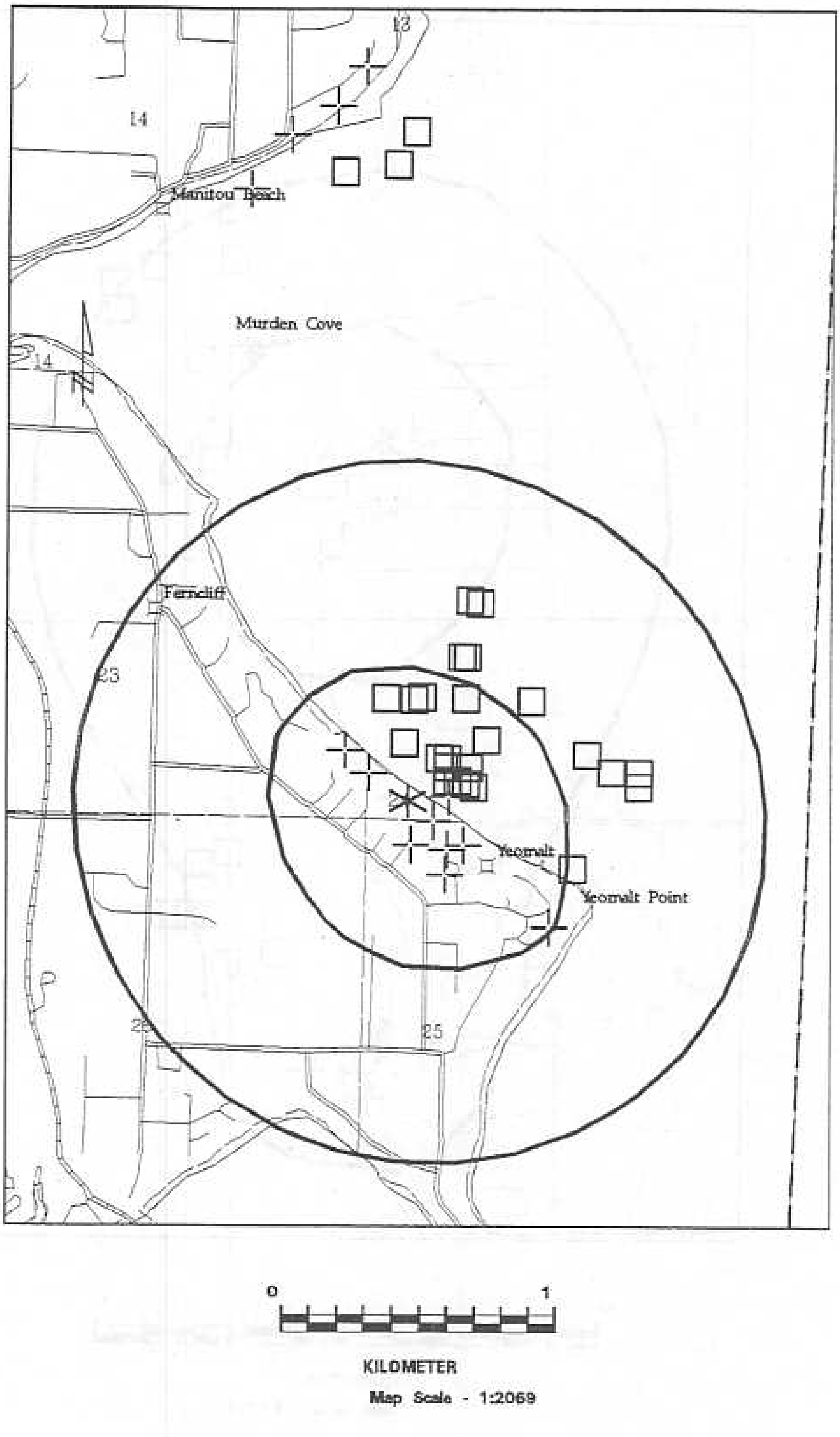
Appendix D. Home range (95% harmonic mean contour; 1.31 km^2) and core areas (56% contours; 0.27 km^2) of the South Point bald eagles on Hood Canal, Washington. Crosses identify perch locations (n = 21), and the star represents the activity center. Each cross or square may represent >1 location.



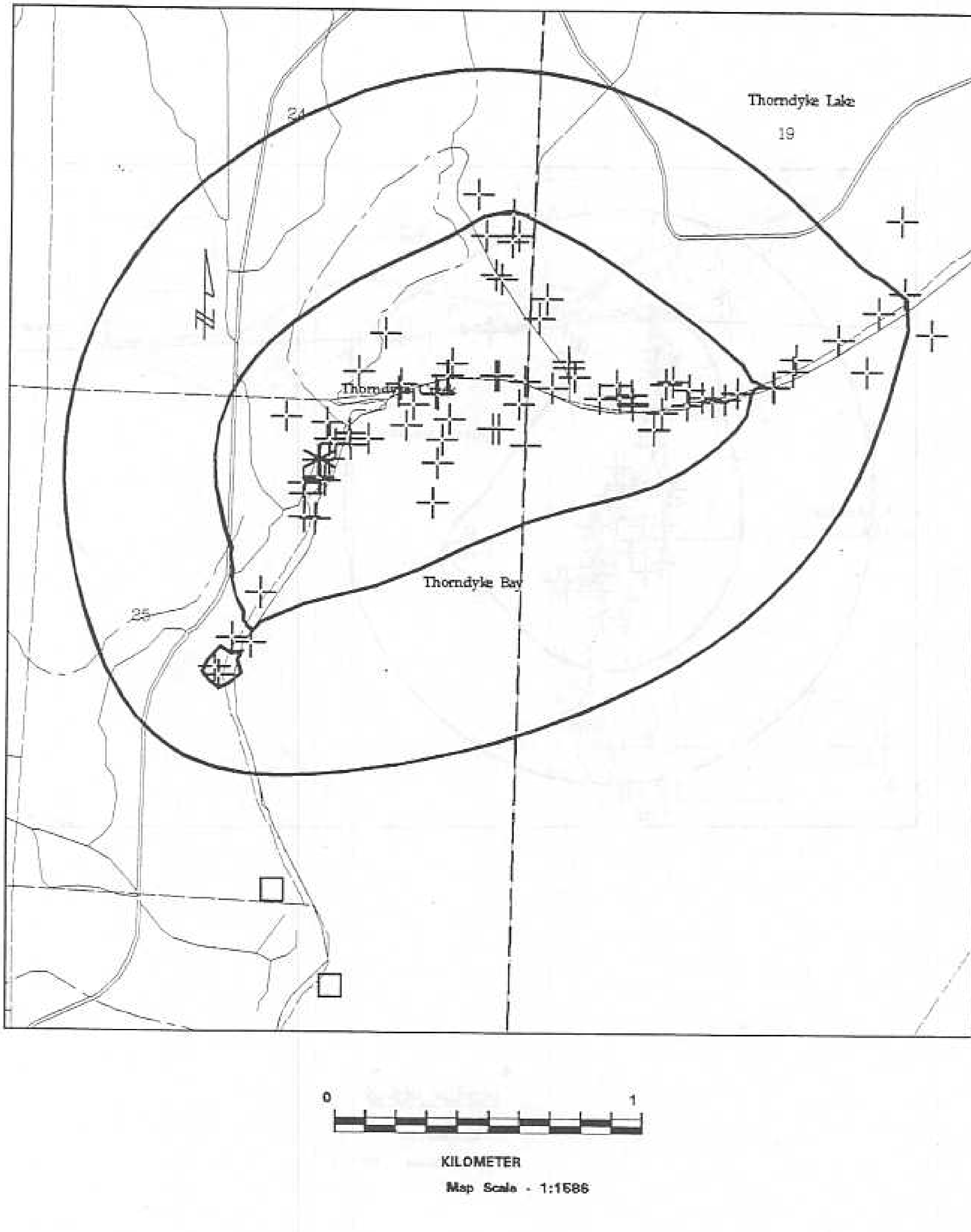
Appendix E. Home range (95% harmonic mean contour; 1.12 km^2) and core areas (56% contours; 0.31 km^2) of the Brown Point bald eagles on Hood Canal, Washington. Crosses identify perch locations (n = 37), squares identify foraging attempts (n = 3), and the star represents the activity center. Each cross or square may represent >1 location.



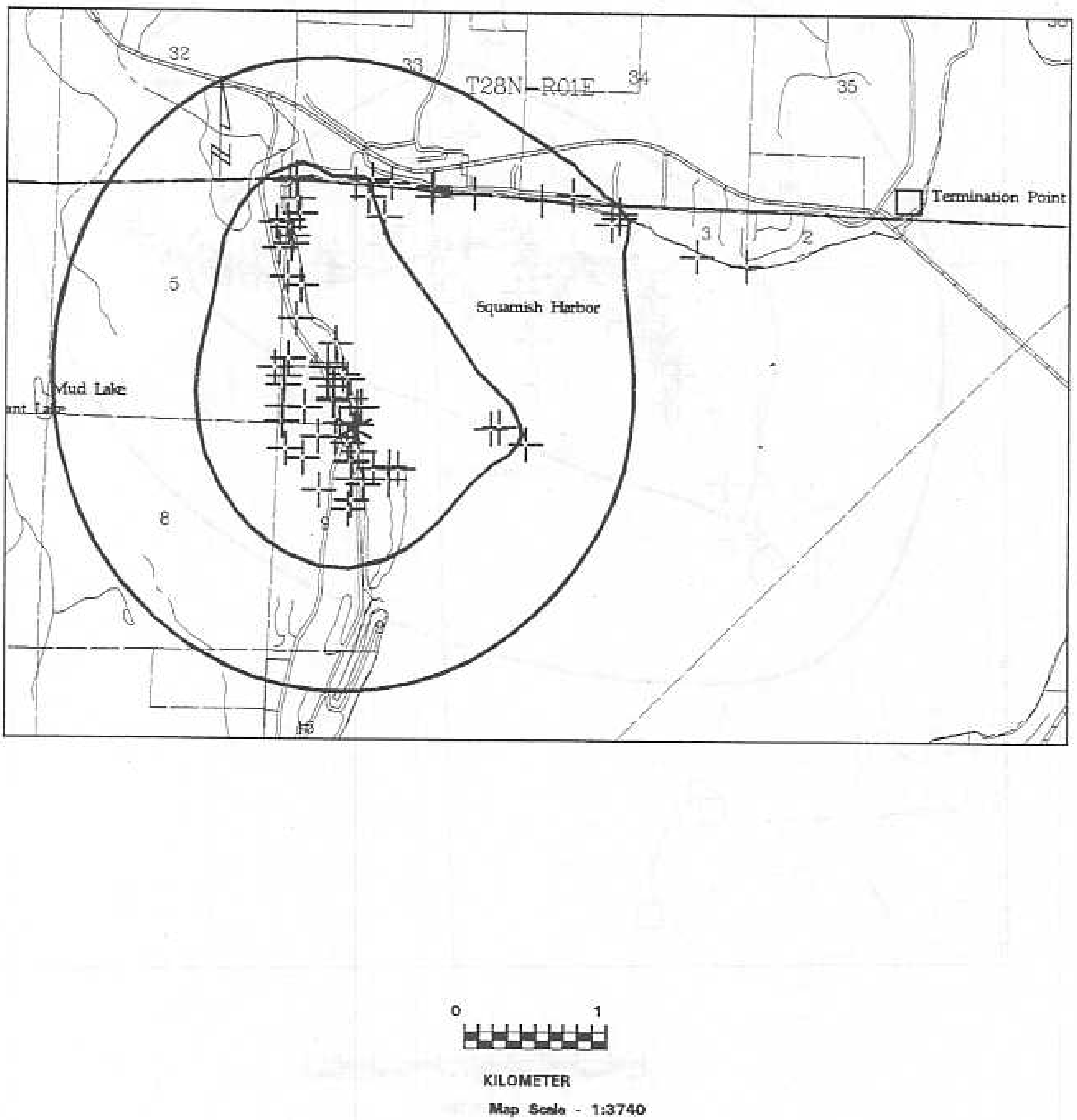
Appendix F. Home range (95% harmonic mean contour; 1.75 km^2) and core area (62% contour; 0.36 km^2) of the Bainbridge bald eagles on Hood Canal, Washington. Crosses indicate perch locations (n = 95), squares identify foraging attempts (n = 24), and the star represents the activity center. Each cross or square may represent >1 location.



Appendix G. Home range (95% harmonic mean contour; 4.99 km^2) and core area (68% contour; 0.93 km^2) of the Yeomalt bald eagles on Hood Canal, Washington. Crosses indicate perch locations (n = 92), squares identify foraging attempts (n = 26), and the star represents the activity center. Each cross or square may represent >1 location.



Appendix H. Home range (95% harmonic mean contour; 4.69 km^2) and core areas (66% contours) of the Thorndyke Bay bald eagles on Hood Canal, Washington. Crosses identify perch locations (n = 904), the star represents the activity center, and the squares represent outlying perch locations excluded from calculations. Each cross may represent >1 location.



Appendix I. Home range (95% harmonic mean contour; 14.10 km^2) and core area (67% contour) of the Squamish Harbor bald eagles on Hood Canal, Washington. Crosses identify perch locations (n = 910), the star represents the activity center, and the square represents an outlying perch location excluded from calculations. Each cross may represent >1 location.